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Thunder Bay Ice Management Program 1979–1985 Overview Report

Prepared for
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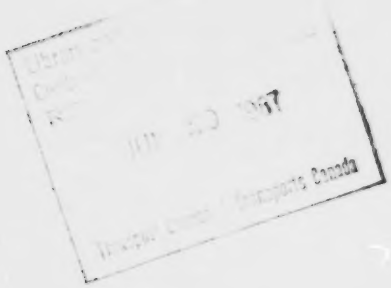

THUNDER BAY ICE MANAGEMENT PROGRAM
1979 - 1985
OVERVIEW REPORT

December 1986

Prepared for the
Transportation Development Centre
by
T.K. Gillies
Communications Gillies Inc.

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17. Abstract

This report gives an overview of the ice management experiments conducted at Thunder Bay between 1979 and 1985. It describes the evolution of several configurations of air bubbler systems and presents comparisons of the systems with respect to operational effectiveness and cost. It describes the development of two computer programs for use by bubbler system designers to define an optimum system for a given slip and by operators to predict the operating time necessary for the system to free the slip of ice respectively. The report also discusses the successful measurement of loads on dock faces due to icebreaker activity in the slips and the evaluation of an innovative vehicle, the Archimedean Screw Tractor, as a support vehicle for ice management.

The report also summarizes the work of two ice management programs conducted at other locations. The first, an ice cutting project whereby patterns are cut in the ice to reduce the size of the ice chunks produced by a ship approaching a dock in ice covered water, and the second, a mechanical ice break and removal technique, whereby ice is cut into blocks that are subsequently tilted and lowered underneath the surrounding ice, leaving an area of open water for a ship to manoeuver.

The findings from this work demonstrate that a bubbler system can be used to ensure that slips in Thunder Bay harbour are free of ice and ready for use at the opening of the navigation season in Lake Superior.

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17. Résumé

Ce rapport fait un tour d'horizon des expérimentations conduites dans le port de Thunder Bay, de 1979 à 1985, sur différents systèmes de maîtrise des glaces. Il décrit les diverses variantes d'un système de déglaçage mettant en oeuvre des diffuseurs d'air, dont il établit un bilan comparatif du point de vue de l'efficacité et du coût. Il décrit également la mise au point de deux programmes informatiques destinés l'un aux bureaux d'étude des systèmes considérés pour leur permettre de définir un système optimal à l'égard d'un bassin de chargement donné, et l'autre, aux exploitants de ces systèmes pour leur permettre de calculer les temps de déglaçage, dans chaque cas. De plus, il fait état des expériences couronnées de succès pour mesurer les forces exercées sur les parois des quais lorsque le déglaçage se fait par un brise-glace, et évalue l'efficacité d'un véhicule amphibie à vis d'Archimède, de type novateur, utilisé pour le soutien logistique.

En outre, ce rapport récapitule les travaux faits dans le cadre de deux programmes pour la maîtrise des glaces, conduits en d'autres endroits. Le premier, consistant à découper la couverture de glaces selon différentes figures géométriques, de manière que la glace se brise en morceaux plus petits que précédemment. Le second, étant une technique de découpage et d'enlèvement des blocs de glace; dans cette technique, la glace est d'abord découpée en blocs qui sont ensuite glissés mécaniquement sous la glace environnante, dégageant ainsi un espace suffisant aux manoeuvres du navire.

Le rapport conclut qu'un système à diffuseurs d'air peut servir au déglaçage des bassins de chargement dans le port de Thunder Bay de manière à les rendre accessibles dès la reprise de la navigation dans le lac Supérieur.

18. Mots-clés	19. Diffusion
Ports, bassins, glaces, maîtrise contrôle, Thunder Bay, diffuseurs d'air, canon pneumatique, véhicule amphibie à vis d'Archimède	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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Thunder Bay Ice Management Program - Executive Summary

The Port of Thunder Bay, Ontario, located on Lake Superior at the western end of the Great Lakes waterway system, has been under pressure over the last decade to expand its port capacities. A guaranteed opening date for terminal facilities, which would correspond to ship channel opening following the ice season, could alleviate this pressure.

To achieve this, it is necessary to increase the melting rate of heavy accumulations of ice on slip faces. These accumulations are caused in part by ships entering the loading berths in the late fall, crushing newly formed ice and pushing it forward into large mounds against the slip.

The report presents an overview of the ice management program of research sponsored by Transport Canada, through the Transportation Development Centre (TDC) and the Canadian Marine Transportation Administration, and aimed at devising and testing various ice management techniques. The program consisted of eight research projects relating directly to Thunder Bay, plus three projects conducted elsewhere which were considered to have application to ice management at Thunder Bay.

Thunder Bay Ice Management Program

The projects at Thunder Bay centered on the use of air bubblers in various system configurations to melt ice. Line, cannon and rake air bubblers were evaluated during the springs of 1979/80 to 1983/84 inclusive, in slips serving the grain elevators of Saskatchewan Wheat Pool, Canadian Malting, United Grain Growers and Manitoba Pool. The bubbler systems were tested in various configurations of a single bubbler and in systems incorporating two types of bubbler. This work was supported by theoretical studies to assess the effect of the environment, both above and below the ice cover, on the ice melt rate during bubbling operations. Additionally, the opportunity was taken to evaluate the effectiveness of the amphibious Archimedian Screw Tractor as a support vehicle for harbour ice management, and to determine the magnitude of loads placed on docks by using an icebreaker or icebreaker/air cushion icebreaking bow to clear ice from elevator slips.

The use of an air bubbler system to free a slip of ice was demonstrated to be effective. The evolution of the system during the testing period advanced the technology from an experimental concept to a reliable ice management tool, in three possible configurations: line, rake and cannon. The basis for choice rests on the geometry of the slip, the

operational procedures of the user and the capital funds available.

Two computer models were developed: one to optimize the bubbler system design for a particular slip, and one to predict the length of time the system must operate to open the slip.

The confidence of the Thunder Bay operators in the findings of this research was demonstrated in 1984 when the Saskatchewan Wheat Pool installed a permanent line bubbler system in a 95-m length of its outshore slip wall as part of renovations to the wall. The operation of this system was subsequently monitored. The findings provided a greater understanding of the natural heat available for ice melting in the slips.

The Archimedian Screw Tractor (AST), a novel amphibious vehicle supported and propelled by contra-rotating helical screws located along its side, proved to be a versatile work vehicle. It was used to break ice up to 0.6 m thick and to transport personnel over ice, snow and previously broken tracks. The AST has a drawbar pull on ice and snow surfaces approximately equal to its own weight; in water it is able to pull about one tonne. In general, the craft was found to provide a stable and safe working platform for ice management and rescue activities.

The dock loading tests demonstrated clearly that shore installations could be placed in jeopardy if a conventional icebreaker is used to break ice in slips. During the tests the CCGS Alexander Henry attempted an icebreaking run into a slip with a 0.7 m thick ice cover. The run was abandoned as the pressure sensors located on the slip face recorded readings in excess of recommended safe loads. When the air cushion icebreaking bow was installed on the Alexander Henry, the slip was broken free of ice without being subjected to undue stress.

Ice Management Projects with Potential for Application at Thunder Bay

Two other techniques for ice management with potential for application at Thunder Bay were also tested under the TDC ice management program. They are:

- patterned ice cutting, and

- mechanical ice break and removal.

Ice cutting , considered as a method of assisting the M.V. Arctic to dock at Little Cornwallis Island in the Arctic, was also reviewed for potential application to Thunder Bay. The objective of ice cutting is to enable a vessel approaching the dock to break ice into pieces sufficiently

small that they can be washed away by the ship's propeller system. Model tests of this technique produced mixed results. Additionally , ships calling at Thunder Bay would not be operating when there was substantial ice cover as is the case in Arctic ports. It was concluded that this technique would require substantially more investigation before it could be used as part of an ice management plan.

A mechanical ice break and removal technique offered researchers a novel approach to ice clearing. The technique involves cutting the ice into blocks, which are subsequently tilted and towed underneath the surrounding ice leaving an area of open ice. The feasibility of the approach, which is only effective for land fast ice, was demonstrated in harbours in Nova Scotia and New Brunswick. A full-scale test conducted at Cameron Beach in Ontario concluded that while the technique might have practical application for the removal of a centre-slip ice section at Thunder Bay, careful orchestration would be required to blend the break and removal technique with bubbler systems.

SOMMAIRE

Au cours de la dernière décennie, l'augmentation du trafic transitant par le port de Thunder Bay, Ontario, a été telle que ce port, situé sur le lac Supérieur à l'extrémité ouest des Grands Lacs, se dirige inéluctablement vers une extension de ses installations, laquelle pourrait être évitée à condition de pouvoir garantir une date de réouverture qui correspondrait à celle des voies navigables.

Pour réaliser cet objectif, il est nécessaire d'accélérer la fonte des importantes accumulations de glace dans les bassins de chargement, accumulations partiellement attribuables aux navires qui, en entrant dans les bassins à la fin de l'automne, brisent la glace nouvellement formée et la poussent devant eux.

Ce rapport présente une vue d'ensemble du programme de recherche sur la maîtrise des glaces qui a été parrainé par Transports Canada, par l'intermédiaire du Centre de développement des transports (CDT) et de l'Administration canadienne du transport maritime, et qui visait l'élaboration et l'essai de diverses techniques de maîtrise de glaces. Le programme comprenait huit projets de recherche se rapportant directement à Thunder Bay et trois autres projets extérieurs dont les résultats pourraient trouver application dans le port de Thunder Bay.

Programme de maîtrise des glaces à Thunder Bay

Les projets de Thunder Bay portaient sur l'utilisation de diffuseurs d'air, dans des configurations diverses, pour faire fondre la glace. Des diffuseurs d'air linéaires, à canon pneumatique et en râteau ont été évalués au cours des printemps de 1979/80 à 1983/84 inclusivement, dans les bassins réservés aux groupes suivants: Saskatchewan Wheat Pool, Canadian Malting, United Grain Growers et Manitoba Pool. Ces diffuseurs d'air ont été évalués en configurations diverses, mettant en oeuvre un seul ou deux types à la fois.

En même temps se déroulaient des études théoriques concernant l'ensemble des facteurs naturels influant sur la vitesse de fonte des glaces pendant les opérations de déglaçage par diffuseurs. De plus, les circonstances ont permis d'évaluer l'efficacité du tracteur amphibie à vis d'Archimède en tant que véhicule de soutien pour la maîtrise des glaces dans le port et de déterminer la poussée des glaces sur les quais lors de l'utilisation d'un brise-glace ou d'une proue brise-glace à coussin d'air pour dégager les bassins.

L'utilisation d'un système à diffuseurs d'air pour le déglaçage dans les bassins s'est révélée efficace. De perfectionnement en perfectionnement pendant la période d'essai, on est passé d'un dispositif expérimental rudimentaire à un outil fiable de maîtrise des glaces en trois configurations: linéaire, en râteau et à canon pneumatique. Le choix de la configuration dépend de la géométrie du bassin, des méthodes opérationnelles de l'utilisateur et des ressources financières.

Deux modèles informatiques ont aussi été élaborés: le premier servait à optimiser la conception d'un diffuseur pour un bassin donné et, le deuxième, à prédire la durée requise d'utilisation du système pour ouvrir le bassin.

Les exploitants du port de Thunder Bay ont confiance dans le système à diffuseurs d'air mis au point; la preuve en a été acquise lorsque la Saskatchewan Wheat Pool a installé, en 1984, un système permanent de type linéaire sur une longueur de 95 mètres dans la paroi extérieure de son bassin, à l'occasion de la rénovation de cette paroi. Le contrôle suivi de l'action de ce système a, par la suite, permis de mieux comprendre le potentiel thermique naturel mis en oeuvre pour faire fondre la glace dans les bassins.

Le véhicule à vis d'Archimède, appareil amphibie de conception nouvelle dont la flottabilité et la propulsion sont assurées par deux vis hélicoïdales tournant en sens contraire et situées sur les côtés du véhicule, s'est révélé un outil de travail des plus adaptables. Il a servi à briser des glaces jusqu'à 0,6 m d'épaisseur et à transporter du personnel, évoluant aussi bien sur glace et sur neige que dans des chenaux partiellement refermés. L'effort au crochet de ce véhicule est environ égal à son propre poids sur la glace et la neige; dans l'eau, il correspond à environ une tonne. Dans l'ensemble, il s'est révélé une plate-forme de travail stable et sûre pour la maîtrise des glaces et les opérations de sauvetage.

Les essais visant à déterminer la pression des glaces sur les parois des bassins ont montré clairement que les installations en place pouvaient être mises en danger lorsqu'un brise-glace classique est utilisé pour déglacer un bassin de chargement. Au cours des essais, le brise-glace canadien Alexander Henry a tenté de déglacer un bassin recouvert d'une couche de glace de 0,7 m d'épaisseur. L'essai a dû être abandonné lorsque les capteurs de pression installés sur les parois du quai ont enregistré des pressions dépassant les valeurs permises. Après l'installation de la proue à coussin d'air sur le navire, le bassin a pu être déglacé sans danger pour les parois du quai.

Projets de maîtrise des glaces applicables à Thunder Bay

Deux autres techniques de maîtrise des glaces potentiellement applicables à Thunder Bay ont également fait l'objet d'essais dans le cadre du programme de maîtrise des glaces du CDT:

- entaille de la glace en configurations diverses; et
- découpage en blocs et enlèvement des glaces.

La première, qui est une solution envisagée pour permettre au N.M. Arctic d'accoster lîle Little Cornallis dans l'Arctique, a été étudiée dans l'optique d'une application potentielle à Thunder Bay. Cette technique permet à un navire qui s'approche d'un quai de briser la glace en morceaux suffisamment petits pour assurer le déglaçage grâce au mouvement de l'hélice. Les essais sur modèles réduits n'ont pas donné de résultats probants; de plus, à Thunder Bay, aucun navire n'est appelé à accoster lorsque les glaces atteignent une certaine épaisseur, contrairement à ce qui se passe dans l'Arctique. On a donc conclu que cette technique nécessiterait une étude plus approfondie avant d'être intégrée à un programme de maîtrise des glaces.

La deuxième technique a ouvert une nouvelle perspective aux chercheurs en matière de déglaçage. Il s'agit en fait de découper la glace en blocs et de glisser ces derniers sous la couverture de glace environnante, créant ainsi une zone d'eau libre. La faisabilité de cette approche, qui n'est efficace que dans le cas d'une glace côtière, a été démontrée dans les ports de la Nouvelle-Ecosse et du Nouveau-Brunswick. Un essai à grande échelle réalisé à Cameron Beach, Ontario, a permis de conclure que, même si cette technique peut avoir des applications pratiques pour l'enlèvement de la glace au centre des bassins de Thunder Bay, une coordination délicate serait requise entre cette technique et celle des diffuseurs d'air.

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1. INTRODUCTION

1.1 Background

The rhythm of marine operations in Canadian waters is largely dictated by the formation and melting of ice in the waterways. The forecast opening dates for various waterways and channels each spring are now established by extrapolating from historical records and by careful deployment of a modern fleet of icebreakers. Ship owners and operators use these forecast dates for route planning aimed at maximizing their operating efficiencies.

It has been observed in recent years that even though channels are clear of ice and available to shipping on forecast dates, access to harbours and ports is frequently barred by large accumulations of slow melting ice on slip faces. These heavy accumulations are in part caused by ships entering loading berths in the late fall, crushing newly formed ice and pushing it forward into large mounds against the slip. The inability of ports to open as early as shipping channels or, in many cases, even to predict accurately when they will open, limits port capacities, and in turn, limits the efficiency of the overall marine transport system.

The Port of Thunder Bay, Ontario, located on Lake Superior at the western end of the Great Lakes waterway system, has been under pressure over the last decade to expand its port capacities. A guaranteed opening date for terminal facilities which would correspond to ship channel opening following the ice season could alleviate this pressure.

For these reasons Transport Canada, through the Transportation Development Centre (TDC) and the Canadian Marine Transportation Administration, has sponsored a program of research aimed at devising and testing various techniques which may have application to ice management in the Port of Thunder Bay to effect season extension.

This report presents an overview of the ice management program of research undertaken by TDC at Thunder Bay since 1979. It also describes the results of two other ice management projects using techniques which could have application at Thunder Bay.

1.2 Program Objective

The overall objective of the program is to contribute to safe and efficient marine operations in seasonally ice-covered waters through the application of technology.

The specific objectives are to devise and test new and more efficient ice management techniques for use in Canadian sub-Arctic waters, particularly in harbours, inland waters and rivers for extension of the shipping season.

1.3 Program Organization

The Transportation Development Centre managed all elements of the research program using funds mainly made available from the Canadian Marine Transportation Administration. Research was conducted at three field locations with each field activity supported by some theoretical laboratory work. The locations were:

- Thunder Bay, Ontario: the effectiveness of air bubbler systems and of novel vehicles to break or melt slip ice was tested. Funds or services were made available from the Lakehead Harbour Commission, Mitsui Inc. and the Canadian Coast Guard. The work was variously monitored and reported by V.B. Cook Ltd., Arctec Canada Ltd. and the Thunder Bay Harbour Commission (formerly the Lakehead Harbour Commission).

- Little Cornwallis Island, N.W.T.: ice cutting techniques were tested as a method of clearing ice from dock faces. The work was conducted by Acres Consulting Services of Calgary, Alberta.

- Nova Scotia/New Brunswick/Ontario mechanical ice break and removal techniques were studied. The work was conducted by Martec Ltd. of Halifax, N.S.

2. THUNDER BAY ICE MANAGEMENT PROGRAM

2.1 General

The program at Thunder Bay centered around the use of air bubblers in various system configurations to melt ice. Air bubblers have been in existence for some time and have been used extensively in waterway operations. However, their primary application has been in protecting lock faces from ice damage and maintaining open channels rather than specifically freeing loading berths of ice. Since 1979 several bubbler systems have been devised and their effectiveness has been evaluated in Thunder Bay slips. This work was supported by several theoretical studies to assess the effect of the environment, both above and below the ice cover, on the ice melt rate during bubbling operations. Additionally, opportunity was taken to evaluate the effectiveness of the amphibious Archimedean Screw Tractor as a support vehicle for harbour ice management and to determine the magnitude of loads placed on docks through the use of an icebreaker or icebreaker/ACIB combination for slip opening in the spring.

Figure 2.1 illustrates the harbour and identifies the various slips participating in the program. The program consisted of the following activities:

- line air bubbler evaluation in the slip serving Saskatchewan Wheat Pool Grain Elevators 1979/80, 1980/81, 1981/82;
- cannon air bubbler evaluation in slip serving Canadian Malting, 1981/82;
- line air bubbler/rake bubbler evaluation in slip serving United Grain Growers Elevator "M" and Manitoba Pool Elevator #1, 1982/83;
- rake bubbler evaluation in slip serving Canadian Malting and Saskatchewan Wheat Pool Elevator 7B, 1983/84;
- cannon air bubbler evaluation in slip serving Canada Malting and Saskatchewan Wheat Pool Elevator 7B, 1983/84;
- dock loading due to the use of an icebreaker and an icebreaker/ACIB combination to clear ice from elevator slips;
- permanent air bubbler system evaluation in slip serving Saskatchewan Wheat Pool Elevators, 1984/85;
- evaluation of Archimedean Screw Tractor.

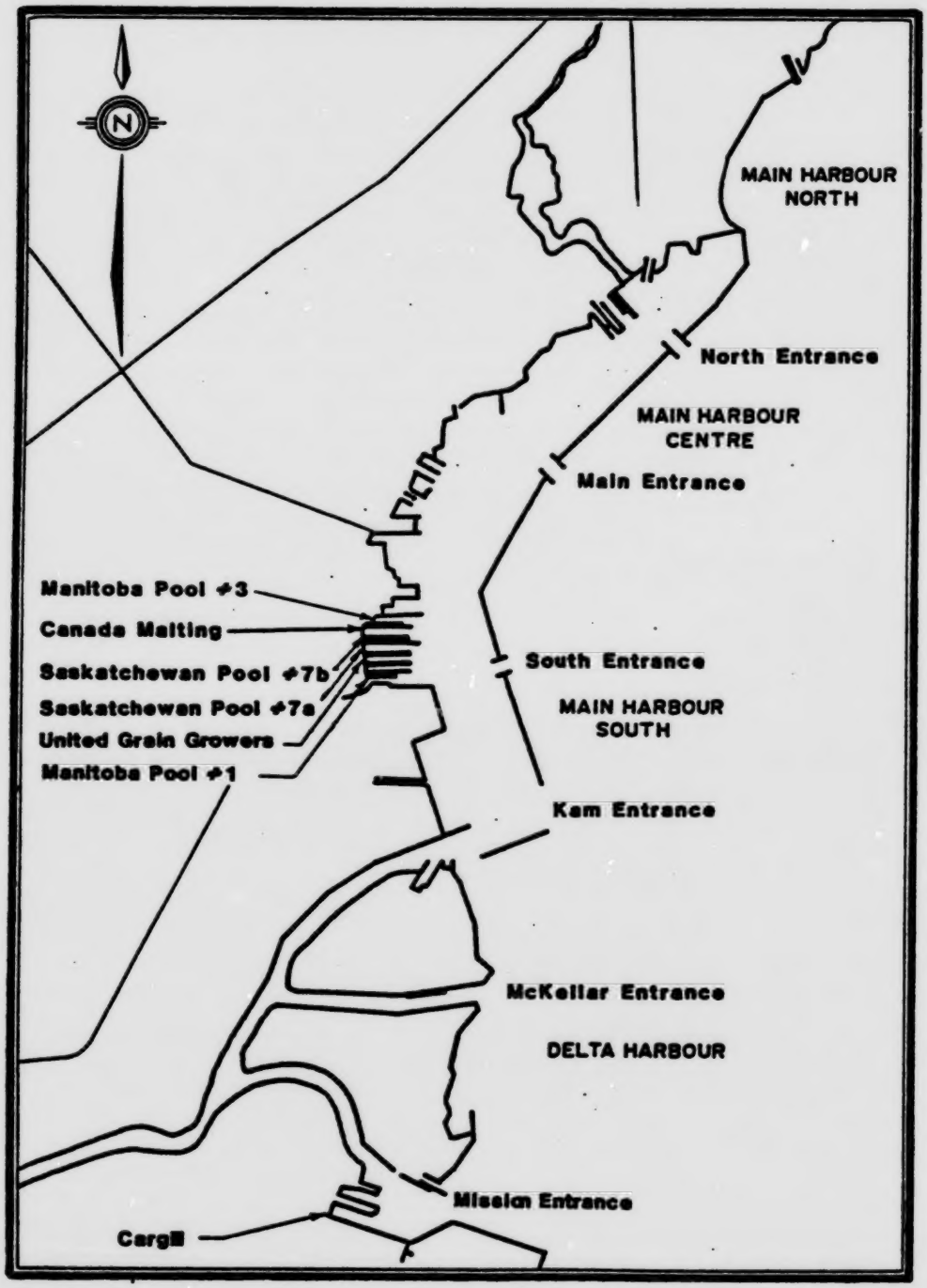


Figure 2.1 Thunder Bay Harbour

2.2 Air Bubbler System Concept Testing, 1979/80 season

2.2.1 General

The work of the 1979/80 season tested the concept of using an air bubbler to melt the spring ice in a slip. The then Lakehead Harbour Commission developed a line air bubbler system and installed it in the Saskatchewan Wheat Pool #7A loading berth for operation in the spring of 1980.

2.2.2 System Design

The system consisted of:

- A perforated pipe delivery network: A three section network (inshore, outshore, centre slip) of flexible, polyethylene, low density, series 75, Type I pipe. The pipe had pre-drilled, 1.6 mm holes spaced at 6 metre intervals.

- A compressor: A Gardner-Denver Model 325 diesel compressor delivering a maximum air flow of 9 m^3/min at a maximum pressure of 7 kg/cm^2.

- Auxilliary Equipment: Electrical heat trace cables inserted into the compressor hoses to prevent freezing when the system was not in use; pressure regulators in the compressor line to each section of the network; fittings and weights as required to keep the pipe network submerged.

2.2.3 Operational Observations

The system was operational between January 25th and March 24th, 1980. During that time the ice thickness was monitored in both the Saskatchewan Wheat Pool test slip and the nearby unbubbled Canada Malting slip.

Figure 2.2 illustrates the ice conditions in the slip during February and March. The open water attests to the ability of the bubbler system to affect the ice cover. As a result of the bubbling, significantly less effort was required on the part of a reinforced-hull tug to break open the Saskatchewan Wheat Pool slip than any other slip in Thunder Bay Harbour.

The problems encountered with the system design included:

- difficulties in establishing optimal pressures for the network: at 1.7 kg/cm^2 only very localized ice melt occurred; at 5.8 kg/cm^2 the compressor became unstable and necessitated the installation of line

Figure 2.2 View of Ice Cover During Bubbler Operation

pressure regulators; at 3.5 kg/cm^2 (with the regulators) the compressor stabilized but several of the line fittings ruptured;

- the elimination of part of the centre-slip line when it became encased in ice;

- the reduced effectiveness of parts of the system due to silt intrusion into the pipes during periods of non-use;

- the eventual destruction of much of the network due to vessel movement in the berth.

2.2.4 Comment

The operational experience of the 1979/80 season demonstrated the potential of the air bubbler concept. Further work on the design of the system and on the methods used to monitor its effectiveness could now be undertaken to determine its commercial value.

2.3 Bubbler System Testing 1981/82 (1)*

2.3.1 General

Between March 1980 and October 1981 several refinements were made to the line air bubbler system by the Lakehead Harbour Commission. The design was considered to be sufficiently advanced to conduct a detailed performance monitoring and evaluation program aimed at devising a technique to predict the number of days the system would be required to operate in order to clear the slip in time for the opening of the shipping season. (The spring of 1981 was so mild that there was neither the opportunity nor the need to conduct field operations with the bubbler system.)

In addition to the line air bubbler installed in the Saskatchewan Wheat Pool slip, a piston bubbler designed by Atara Corp. was installed for testing in the Canada Malting slip.

2.3.2 Refined Line Air Bubbler System

a) System Description

The line air bubbler system installed for the 1981/82 evaluation is shown in Figure 2.3. Two 40 hp. Grimmer Schmidt compressors, rated at 300 m^3/hr. of free air at 690 kPa, provide the compressed air supply.

* **See references**

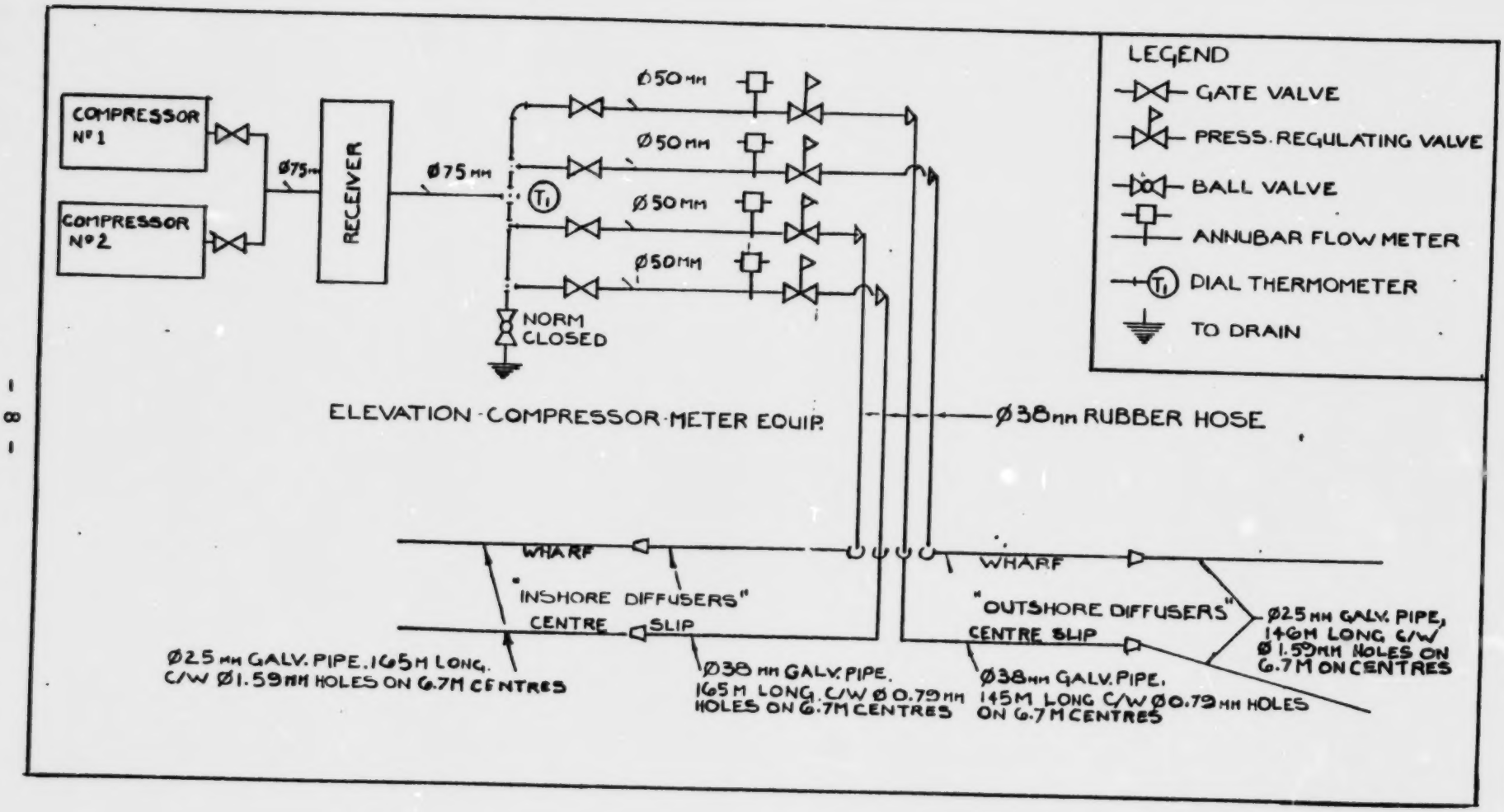


Figure 2.3 Saskatchewan Wheat Pool 7A Installation

The two compressors discharge to a 75 mm pipe manifold and into a 0.28 m^3 receiver. The 75 mm outlet from the receiver feeds four air metering stations, each connected to a branch of the system. Air from the receiver feeds a 75 mm header and is split into four parallel branches. The air temperature is measured in the header. A condensate trap and drain valve are located at the bottom of the header for periodic cleaning.

Each branch of the air metering station is fabricated from a 50 mm diameter pipe and includes a 50 mm isolation valve, an annubar flow sensor device and a pressure regulating valve. A portable "Eagle Eye" flow meter connects to each annubar device. Each branch is connected to the distribution pipe consisting of two parts: the delivery section and the diffuser section.

The delivery section consists of approximately 6 m of 38 mm rubber hose. It is connected to a verticle pipe attached to the side of the wharf. This pipe is internally heat traced and carries the air from the top of the wharf to the bottom of the slip.

The diffuser sections are connected to the bottom of the vertical pipes and rest on the slip bottom. Each diffuser is made up of two parts: the first a 38 mm galvanized pipe with 0.79 mm holes drilled in the pipe wall at 6.7 m centres; the second 25 mm galvanized pipe with 1.59 mm holes drilled in the pipe wall at 6.7 m centres. The diffusers are up to 330 m long.

b) Operational Observations

After initial testing and some minor repairs, the system was operated from February 27th until April 1st, 1982. During this time the following parameters were monitored with varying degrees of success.

- Air pressure and flow: an attempt was made to set and regulate the air flow in each branch at 127m^3/h (standard air). This was not possible due to the inability of the 0.28 m^3 receiver (surge tank) to smooth out the surges from the compressors. Branch flows cycled from 100 to 136 m^3/h. The pressure regulating valves did not operate consistently and the gauges gave incorrect readings.

- Climatic conditions: the severity of the winter conditions was established from meteorological data published by Environment Canada from Thunder Bay Airport. From hourly temperature readings the Freezing Degree Days (below 0°C) and Thawing Degree

Days (above 0°C) were calculated. The temperature difference between the lakeshore and the airport was small enough to be ignored.

- Water temperature: water temperature was taken at the diffuser outlet by a thermometer lowered to the bottom of the slip.

- Ice thickness: a 39 station grid was established to critically monitor the ice growth and melt. A direct method of cutting a slot and using a wire to measure ice thickness was employed until thin ice prohibited this technique for safety reasons. Photographs were then taken of the ice surface and used to estimate the rate of deterioration.

- Energy requirement: a rough estimate of the compressor power consumption was made using periodic hour meter readings on the motors. The power consumption during the test period was approximately 1240 kwh/day.

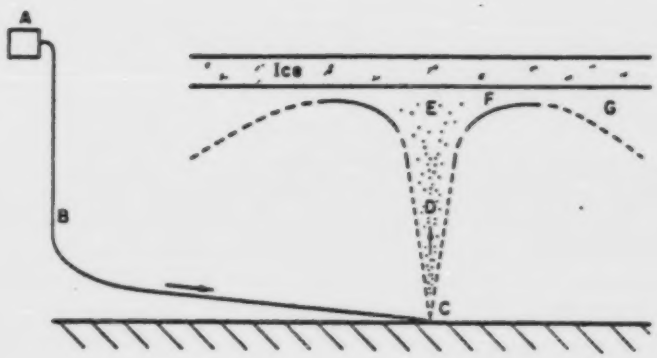
c) Comment

The operational experience with the line air bubbler in the 1981/82 season demonstrated that while the design was greatly improved over the 1979/80 season some of the original problems still persisted. The holes in the diffuser sections still silted up and the centre slip section of the diffuser was at great risk from manoeuvring ships.

The monitored data collected proved to be most useful as a first step in defining the theoretical operation of the system. Stephan's formula for predicting natural ice growth was modified and a formula created to predict ice growth with initial ice thickness. Using ice thicknesses measured, the rate of growth was calculated for various initial thicknesses. Using the corresponding cumulative freezing degree days for the period, the ice growth was predicted for a variety of measured conditions. Good correlation was obtained between actual and calculated values.

A technical paper entitled "Air Bubbler Systems to Suppress Ice" by George D. Ashton, describes an anlaytical procedure to predict the effectiveness of a bubbler system under various physical conditions. Figure 2.4 shows a schematic diagram of an air bubbler system operation described by Ashton.

Following the Ashton procedure, and using data from the centre slip diffuser line, calculations were made to establish:



(AFTER ASHTON)

A -COMPRESSOR

B -AIR SUPPLY LINE

C -DIFFUSER LINE

D -RISING PLUME OF ENTRAINED WATER

E -PLUME SPREADS UNDER ICE SURFACE

F -REGION OF HORIZONTAL FLOW OF PLUME

G -DISSIPATION OF ENTRAINED WATER

Figure 2.4 Schematic Diagram of Diffuser Bubbler System Operation

- the width of the impingement region on the under surface of the ice, 0.83 m;
- the heat transfer rate on the under surface of the ice, 350 watts/m^2;
- the melting rate at the centre line of the impingement region, 100 mm/day.

The rate of melting decreases outward from the centreline of the impingement region. Ashton shows a relationship between the heat transfer rate and the distance from the impingement region. From this relationship ice melting rates were computed for the Saskatchewan Wheat Pool system.

The calculations are valid for conditions when the ice is not thickening, when the air temperature above the ice is near 0°C. If the air temperature falls significantly below freezing, the ice only melts on the undersurface until an equilibrium thickness is attained. Ashton's procedures predict equilibrium ice thicknesses for various surface air temperatures.

There was sufficient correlation between calculated and measured ice melt in the slip due to the bubbler operation to provide a measure of confidence in the calculated heat transfer rate of 350 watts/m^2 for the system in the impingement area.

Based on the data from the 1980/81 work, a preliminary prediction graph was developed for use in estimating the number of days required to operate a specific bubbler system prior to the start of the shipping season.

2.3.3 Atara Air Cannon Bubbler

The "Atara Air Cannon Bubbler" (Figure 2.5) is a device which propels fluid by means of a rising piston of air. A bubble generator located at the base of the tube emits, at regular intervals, a large bubble of air. The bubble rises in the tube drawing replacement fluid into the tube behind it. The bubble exits from the top of the tube entraining an increasingly larger volume of fluid as it ascends to the surface. The flow of air and water produced by the apparatus impinges on the ice cover resulting in thermal erosion of the ice.

These piston mixers offered several advantages; they used low pressure 7½ hp blowers for the air supply and they could be installed through the ice and then removed from the slip for the shipping season.

Figure 2.5 Atara Air Cannon Bubbler

a) System Description

Five air cannons, ranging in length from 0.6 to 5.8 metres, were positioned in the slip adjacent to the Canada Malting Company elevator. A 38-station ice thickness measuring grid was superimposed on the five air cannon stations.

A 7½ hp blower supplied the five air cannons with air at delivery pressures of 83 to 90 kPa. The rate of air supplied varied from 10 m^3/h in cannons 4 and 5, to 24 m^3/h in cannon number 3. The complete air delivery system was compact and easy to handle.

b) Operational Observations

The air cannons were installed on March 5th through holes cut in the ice. The system was operated from March 5th to April 14th. During this time climate conditions and ice thickness was monitored.

The system operation was trouble free and the five cannons were easily retrieved at the end of the test. Figure 2.6 is a photograph taken of the slip during the test period.

Both photographs and observations showed that until almost the end of the monitoring period the perimeter of the holes produced by the air cannons remained vertical as the holes expanded. The hole growth rate was very much affected by volume of air used (varying directly with the volume) but the length of the air cannon barrel did not have any significant effect.

c) Comment

Applying the same analysis to the measured and observed data from both the air cannon and the line air bubbler, the system performance for each is expressed as:

$$R = \frac{(T \times A) + U}{N \times V}$$

where R = rate of ice deterioration $m^3/day/m^3/h$ standard air

T = initial ice thickness; m
A = area of open water; m^2/m
U = volume of ice melted due to sloping sides around open water m^3/m
N = number of days
V = air volume; $m^3/h/m$

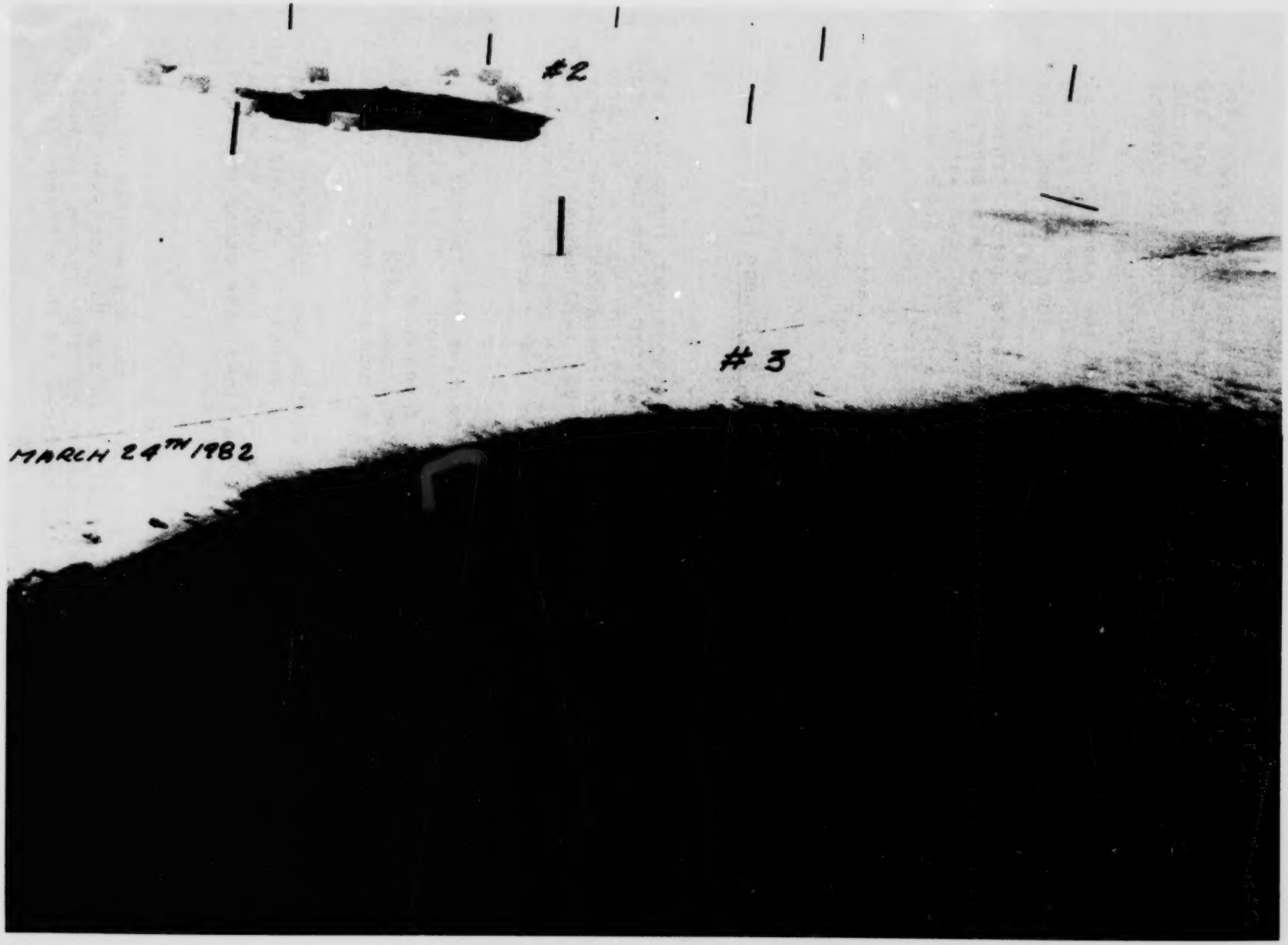


Figure 2.6 Atara Air Cannon Bubbler in Operation

The R for the line bubbler becomes 0.86 m^3/day per m^3/h standard air, compared to 0.26 m^3/day per m^3/h for the air cannon. Thus based on this performance criteria, in the configurations of the test installations, the air cannons were less effective than the line air bubblers.

Researchers believed, however, that the almost vertical ice edges around the open water holes in the air cannon system indicated a significant heat loss through the installation hole directly above the air cannon. This conclusion is supported by G.P. William's paper "Thermal Regime of Lakes and Rivers with Reference to Air Bubbling Systems". In contrast, the edges around the open water of the line air bubbler were tapered at a shallow angle under the ice.

In terms of power consumed, the air cannon was significantly more energy efficient than the line air bubbler.

2.4 Bubbler System Testing 1982/83 Season (2)

2.4.1 General

The bubbler system tested this season was installed in the slip between the Manitoba Pool Elevator #1 and the United Grain Growers Elevator "M". The system was a further refinement of the system installed in the Saskatchewan Wheat Pool slip in 1982 and featured a novel replacement for the troublesome mid-slip bubbler which, though effective, was very expensive to maintain due to its susceptibility to damage from ship operations.

A major effort was made to determine the thermal budget of various slips in the Thunder Bay Harbour. This work was conducted by Arctec Canada Ltd. through a measurement of water temperatures in three slips, one with a two-line bubbler system, one with a one-line bubbler system and one with no bubbler system.(3)

Work was also undertaken to develop two computer models to simulate bubbler systems. One model to optimize the physical and operating parameters of any line bubbler whose approximate configuration can be defined; the other model to predict the performance of the system.

2.4.2 System Design

The line air bubbler portion of the system (See Figure 2.7) was similar to that installed in the Saskatchewan Wheat Pool slip in 1982. Refinements to the system included doubling the diameter of the orifices in the diffuser lines

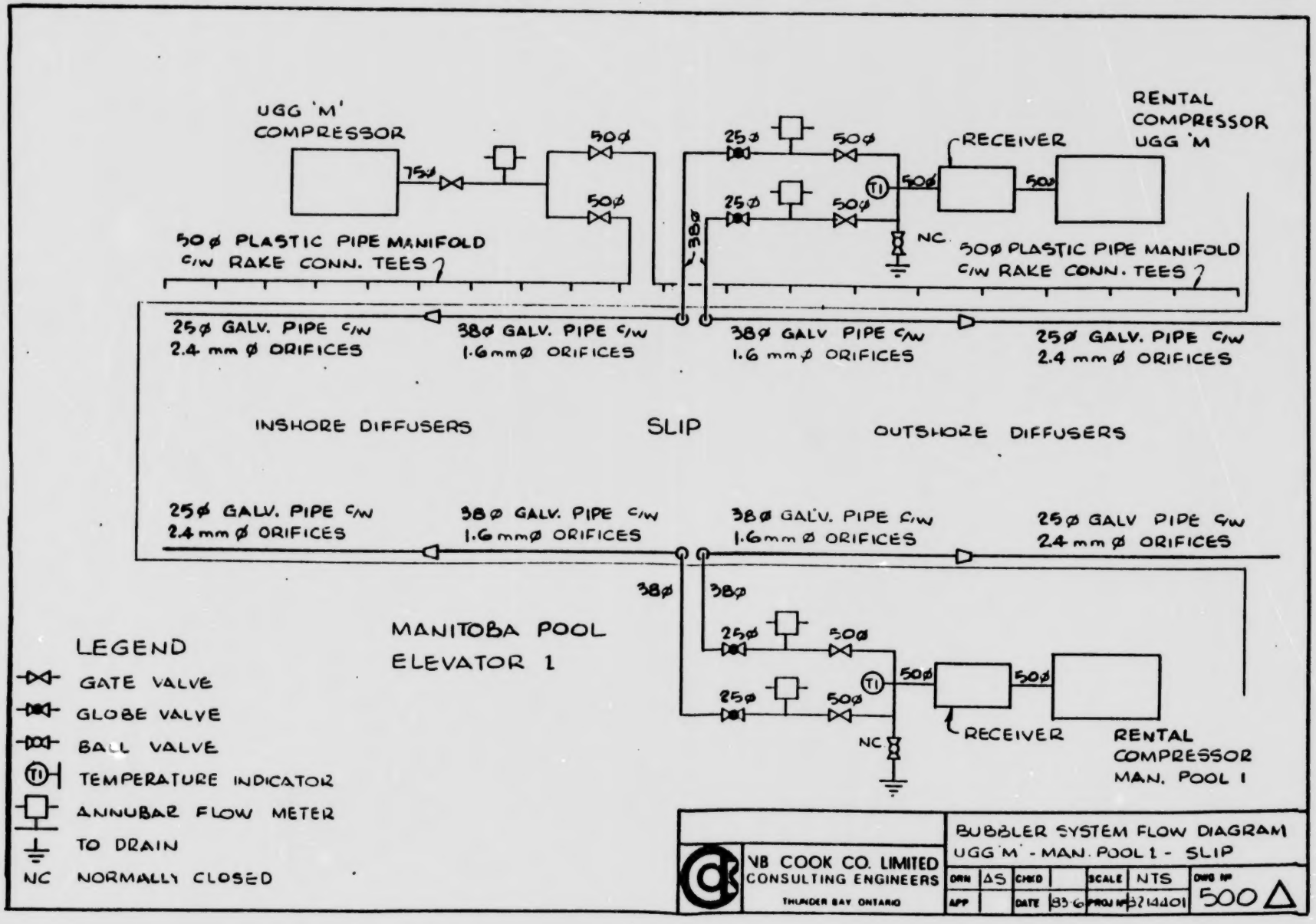


Figure 2.7 Manitoba Pool Elevator Slip Installation 1983

to increase the air flow and to reduce the possibility of the orifices silting up, and replacing pressure regulating valves with globe valves and pressure gauges.

The centre slip diffuser was in the form of a series of rakes (see Figure 2.8). These "rakes" consisted of diffuser pipes supported by barrels set up in a sled-like configuration. The rakes were set below the edge of the ice cover and were individually pulled across the slip at a rate dictated by the rakes capacity to melt ice.

Six rakes were fabricated, three for use inshore and three for use outshore. Air for the rakes was provided by a 75 hp Atlas Copco unit rated at 370 m^3/h free air at a nominal pressure of 690 kPa. The compressor fed a plastic manifold which in turn fed the mid-slip rakes.

2.4.3 Operational Observations

A control set of ice thicknesses was established February 27th, 1983 and the system was then operated until March 24th. During that time the following operational observations were made:

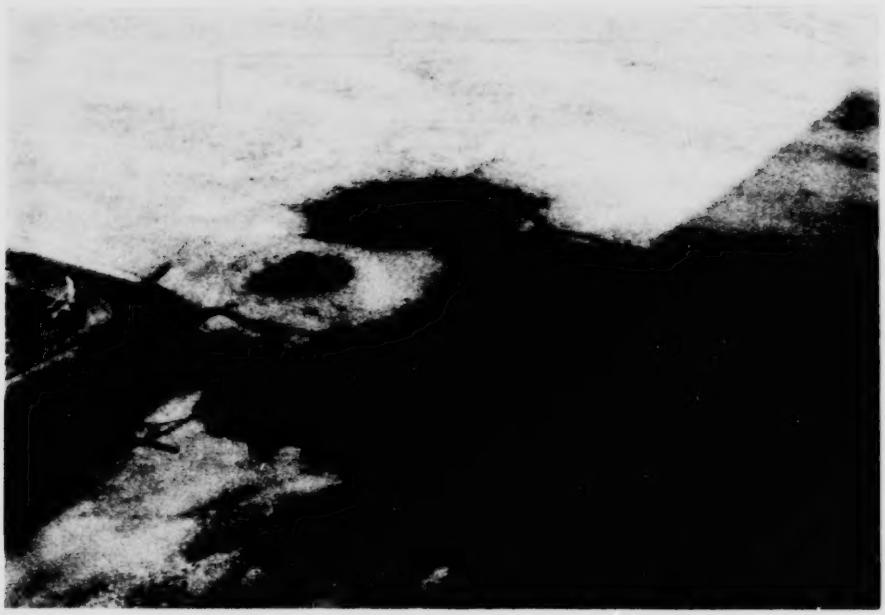
- "Rake" bubbler: because of inadequate draining of condensation, the inshore plastic manifold and rakes quickly froze and were removed from service on March 11th.

- Air pressure and flow: it was found that the new air metering components had to be protected from the severe cold to function well. No trouble was experienced after the stations were housed or relocated indoors. The station configuration used to feed the plastic header pipe, which in turn fed the "rakes", was totally inadequate. Individual metering of each "rake" would seem to be required.

- Climatic conditions: the method established in 1982 to determine the severity of the winter climate was used for 1983.

- Water temperature: for the first time a detailed field survey of water temperature was made over a four day period, March 21st to March 24th. The survey took temperature profiles in three slips, two with bubblers operating and one unbubbled slip. Figure 2.9 shows the locations at which temperature profiles were taken. Each profile consisted of recorded water temperatures under the ice at one meter intervals. The observations made during the four day survey demonstrated that:

Mid-Slip Diffuser (Rake) Propagation Test



Parallel Rakes in Operation

Figure 2.8 Mid-slip Rake Diffuser

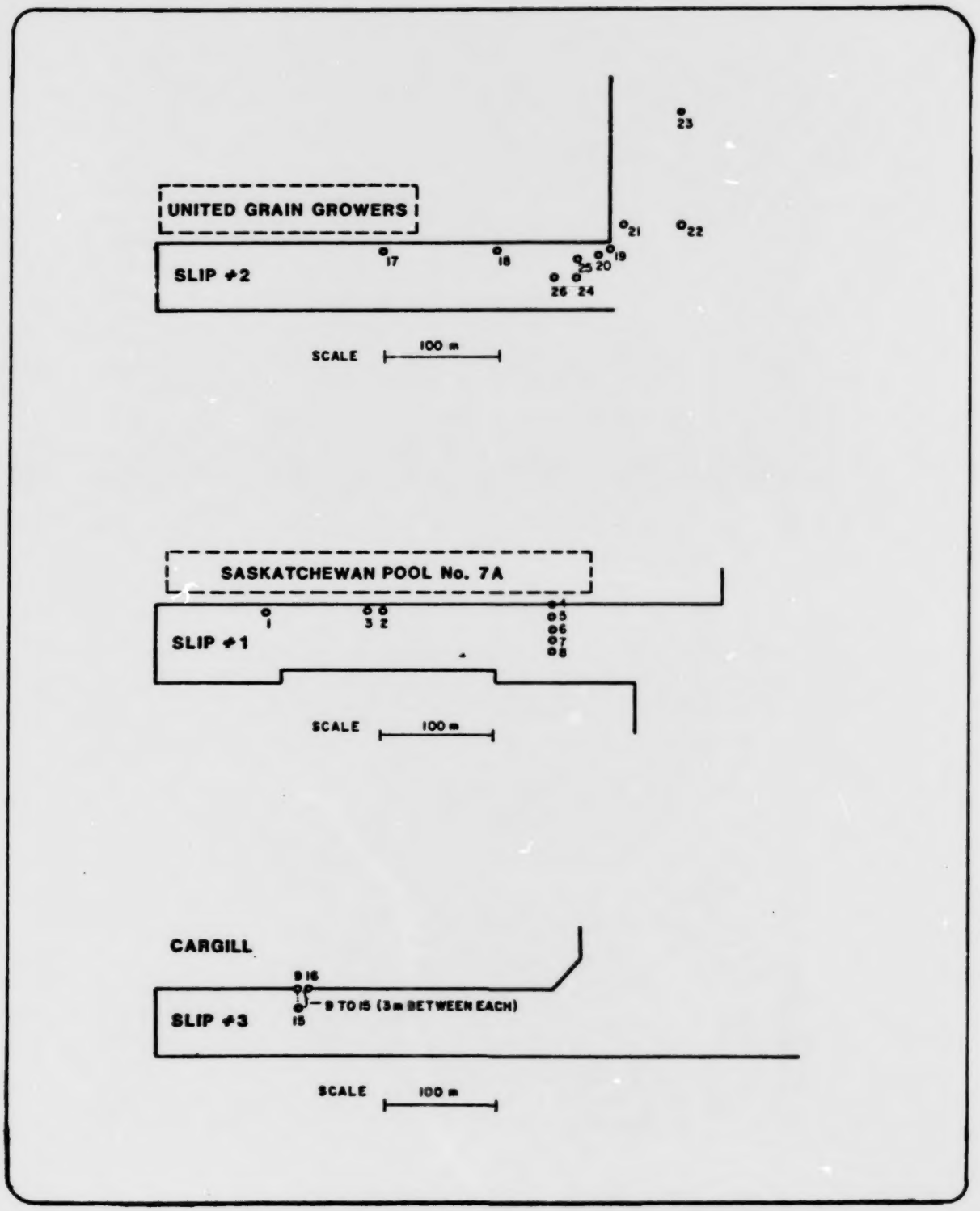


Figure 2.9 Temperature Sensor Locations in Test Slips

- water temperature in bubbled slips was between 0.1 and 0.3°C while in the unbubbled slip it was approximately 1.0°C;

- water temperature was almost constant with depth;

- water temperature was constant in each slip over the four day survey period except for an unexplained temperature increase in slip #3;

- water temperature was lower in the centre of the slip relative to the temperature measured at the slip port entrance (see Figure 2.10).

- Ice thickness: the method established in 1982 to monitor ice thickness was used for 1983 over a 39 station grid.

- Power consumption: watt meter readings were taken from the compressors. The Manitoba Pool bubbler compressor consumed 494 kwh/day, the UGG "M" bubbler compressor consumed 552 kwh/day and the outshore rake compressor consumed 779 kwh/day.

2.4.4 Comment

a) Thermal Budget of Slip

From the measurements taken it was determined that the thermal budget of the slip is sufficient to melt 80 mm of the ice thickness. Assuming that the ice is 0.75 m thick and that there is no heat loss or gain during the bubbling period, only 10.7% of the ice volume will be melted. The air bubbler experiments prove that additional heat is available to the slip probably from the deeper water of the bay as well as from the ground and wharf walls.

b) Forecasting Models

Two computer models were developed, one for use by future designers to specify a bubbler system for a specific slip and the other to predict the performance of the system so that an operational start-up date can be established for each season.

The first model relates the controllable parameters e.g. air flow, pressure and to the physical constraints of the slip eg. depth, length. The model is based on the thermodynamic concept of reversible, adiabatic flow of an ideal gas through a nozzle. The simulation starts at the beginning of the diffuser section so that the initial conditions to this point must be calculated.

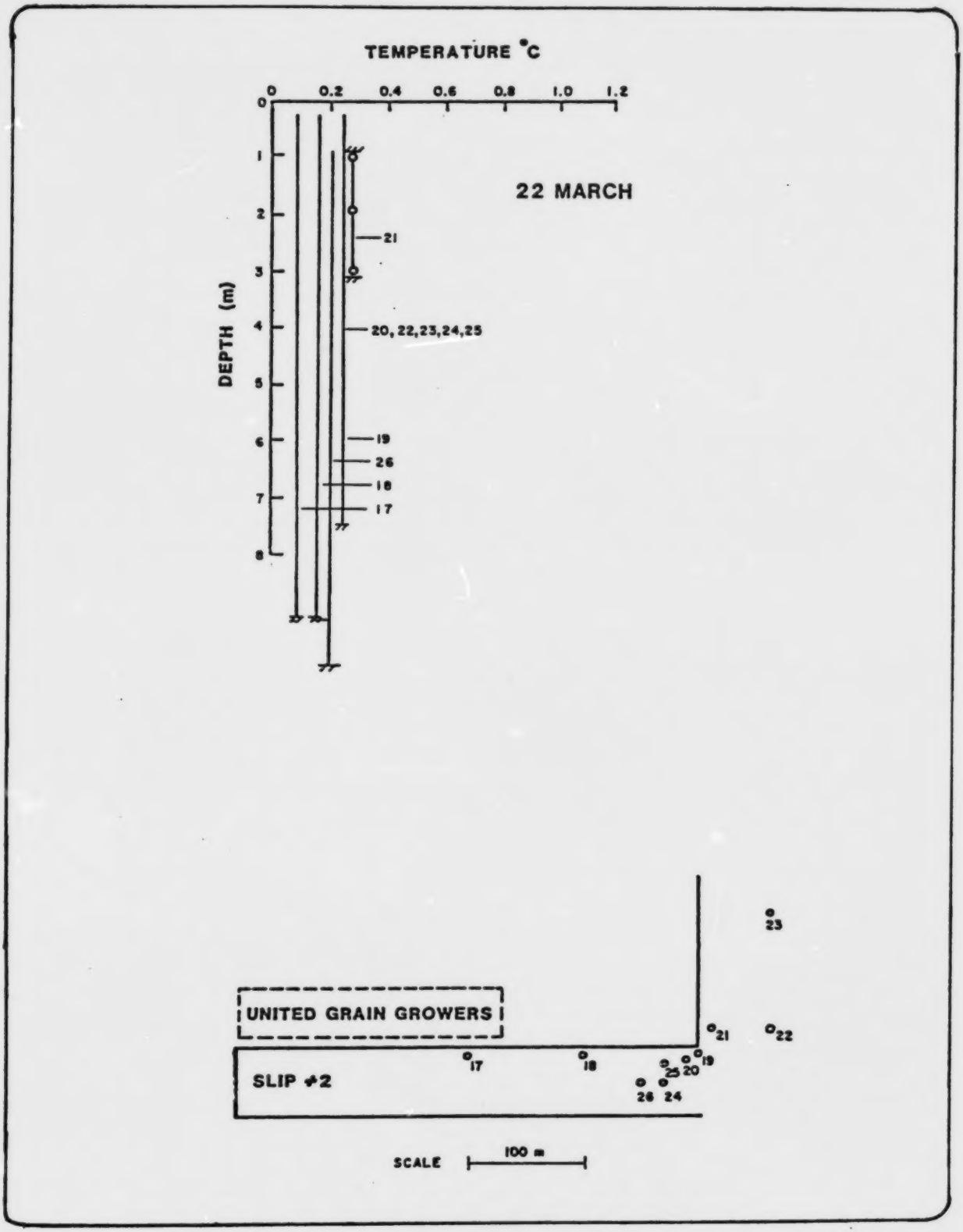


Figure 2.10 Effect of Location on Temperature in Slip

The second model predicts the growth/decay of ice. The model is based on Ashton, as outlined in "Air Bubbler System to Suppress Ice".

The measured performance of the line bubbler and the predicted performance using the program developed correlates to an accuracy of approximately 5%.

These models are appropriate for use to design a bubbler system for a harbour slip and to specifically predict when that slip would be available to shipping at the start of the season.

c) "Rake" Bubblers

The rake bubblers were not effective during the 1983 season.

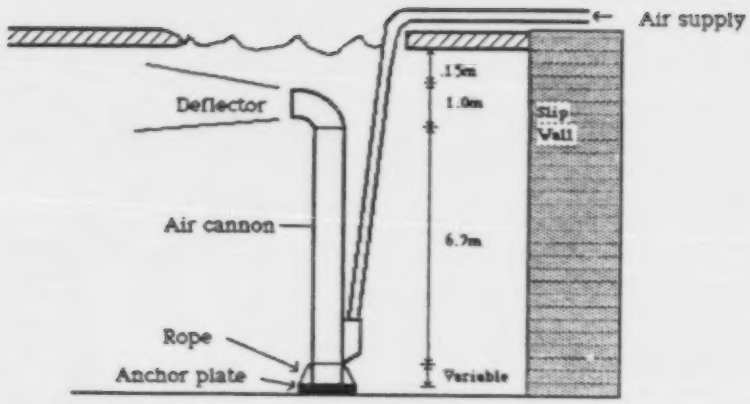
2.5 Bubbler System Testing 1983/84 Season (4)(5)

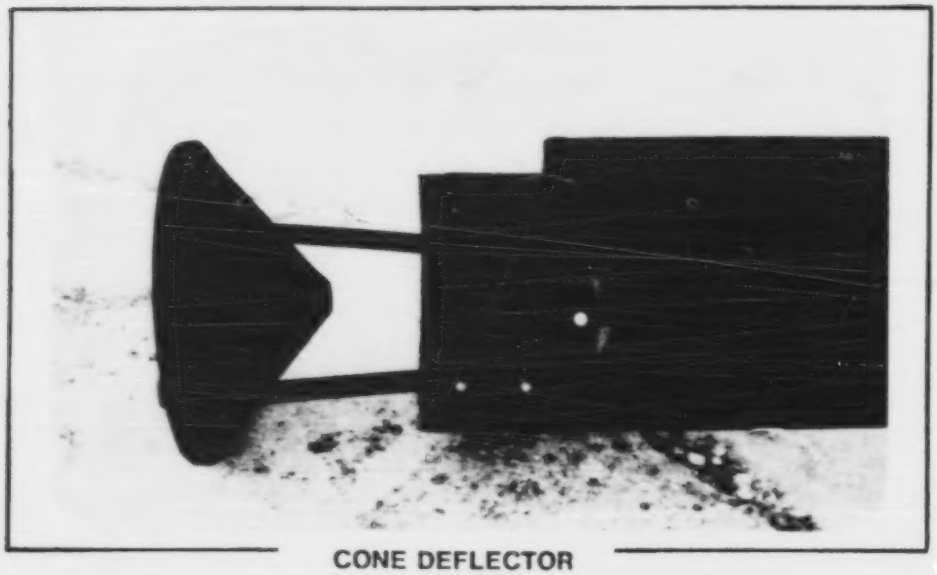
2.5.1 General

By the spring of 1984 a satisfactory bubbler system for mid-slip use had not yet been defined. The rake bubblers, which had not performed well the previous year at the test site, had a history of successful operation in other slips at Thunder Bay. It was decided to install a rake bubbler system for additional testing in 1984.

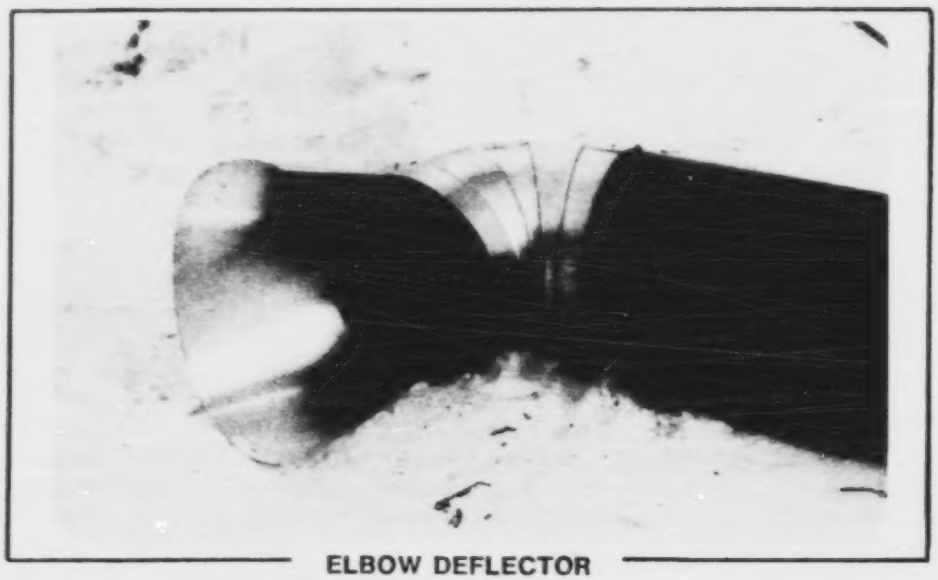
Researchers also turned again to the Atara air cannon bubblers which had been tested in 1982. As with the rakes, cannon air bubblers were less prone to damage as they could be easily removed before ships entered the berth. Also the theory of bubbler operation suggested that cannon bubblers are more efficient at inducing vertical water currents. Previous findings had indicated that a great deal of heat was lost to the atmosphere through the ice hole used to install the air cannons thus contributing to their poor performance. By developing an air cannon with a deflector mounted at the end of the cannon (see Figure 2.11) to direct the entrained warmer water behind the air bubble under the ice cover, it was thought that a better performance might be achieved.

Comparative model tests using point bubblers, a standard cannon bubbler and an air cannon bubbler with a deflector attached were conducted at Arctec Canada laboratories during the months of November and December 1983. In the spring of 1984 two bubbler systems, one using a "rake" bubbler and the other an air cannon bubbler, were installed in the slip between the Canada Malting Co. and the Saskatchewan Wheat Pool Elevators.





CONE DEFLECTOR



ELBOW DEFLECTOR

Figure 2.11 Atara Air Cannon Bubbler With Deflector

2.5.2 Model Tests of Bubbler Systems (6)

A series of laboratory experiments was undertaken to assess the flow development and heat transfer capabilities of the Atara air cannon bubbler. The tests included monitoring of airflow rates, water temperatures, ice thicknessess and water velocities. A range of temperature regimes and three bubbler types (standard air cannon, air cannon with deflector and conventional point source bubbler) were used to compare relative effectiveness.

The experiments were conducted by Arctec Canada Ltd. at their laboratory in Kanata, Ontario. Figure 2.12 illustrates the test set-up used and Table 2.1 describes the Test Basin characteristics. The conclusions reached through these experiments were as follows:

- For flow development: the cannon bubbler with deflector resulted in ice melting to a greater radius than for the other bubblers tested. Comparison of actual and calculated horizontal flows showed that the bubbler performed better than predicted by the model in terms of flow development.

- For heat transfer: the cannon bubbler with deflector melted more ice than did the cannon with a vertical discharge pipe or a point source bubbler under similar conditions.

- For Thunder Bay: the air cannon with deflector had good potential for use as a mid-slip diffuser.

2.5.3 Air Cannon, Bubbler System (Figure 2.13)

An array of 10 air cannon bubblers with deflectors was installed in the Canada Malting Slip together with a thermistor array for temperature measurements (see Figure 2.14). Temperatures were recorded automatically at ½ hour intervals from March 8th until March 10th and then at 2 hour intervals until March 22nd. These data were recorded directly on floppy disks using a portable data acquisition system. Air was supplied from a central 20 hp, 575 volt blower which maintained a system pressure of 76 kPa at 0.132 m^3/s. This maintained a mean water flow of approximately 2 m^3/s per bubbler. Air was supplied to the system from March 9th until March 22nd, 1984.

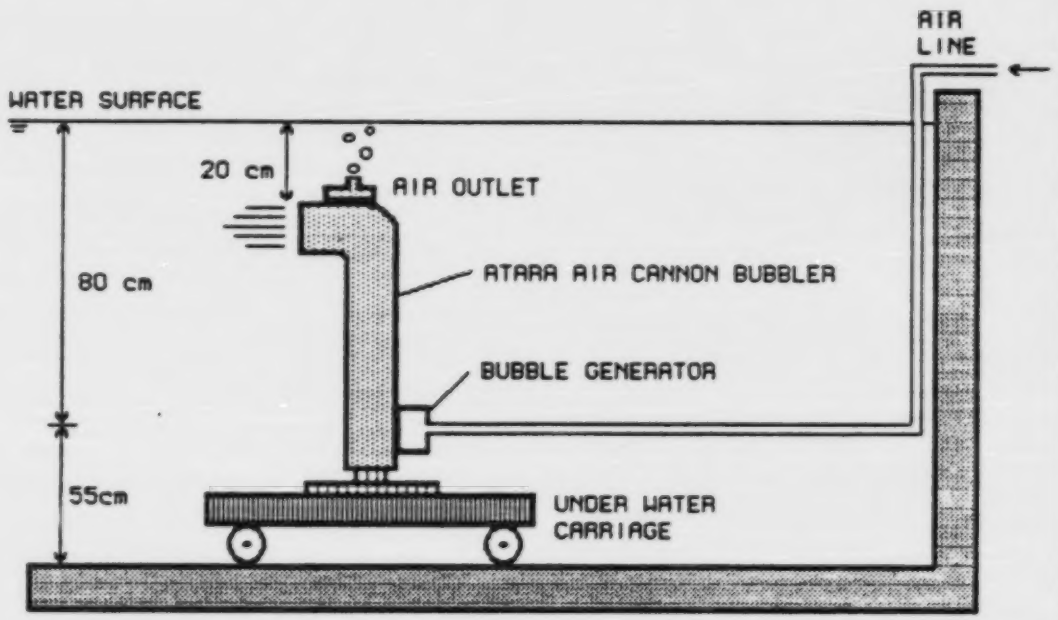
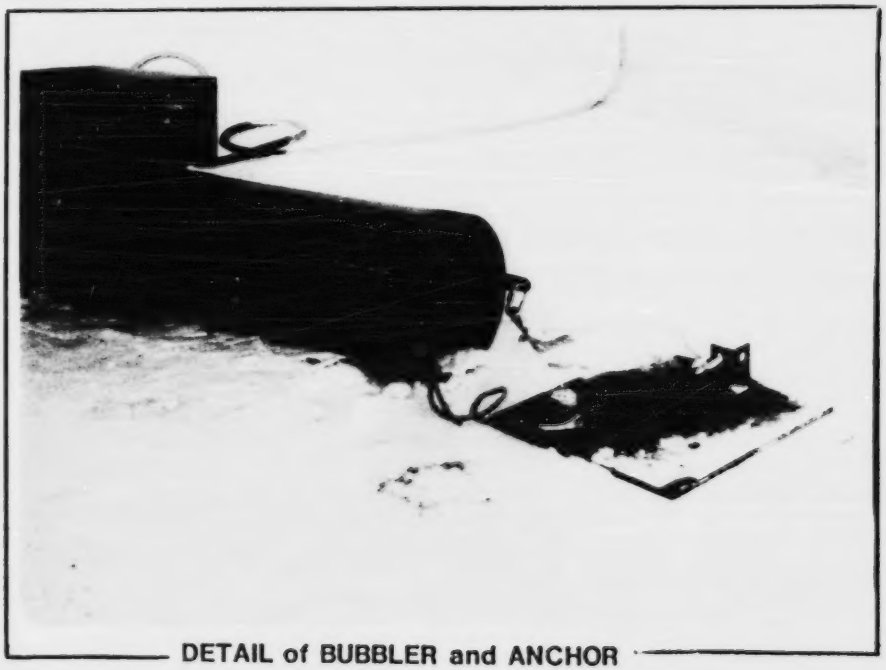


Figure 2.12 Laboratory Test Set-up

TOWING BASINS	BASIN NO. 1 KANATA
Basin	
Length	30.5m 100'
Width	4.9m 16'
Depth	1.5m 6'
Towing Carriage	
Drive System	5 hp
Maximum Load	2.3 tons
Speed Range	0.006-1.3 m/sec
Wavemaker	Electro-Mechanical
Ice Preparation Method	Freezing with Liquid Nitrogen or Conventional Refrigeration Plant
Ice Preparation Capability	6 mm/hr
Temperature during Preparation	to - 75°C
Temperature during Testing	0 to -20°C

Table 2.1 Test Basin Characteristics

COMPLETE BUBBLER UNIT



DETAIL of BUBBLER and ANCHOR

Figure 2.13 Cannon Air Bubblers

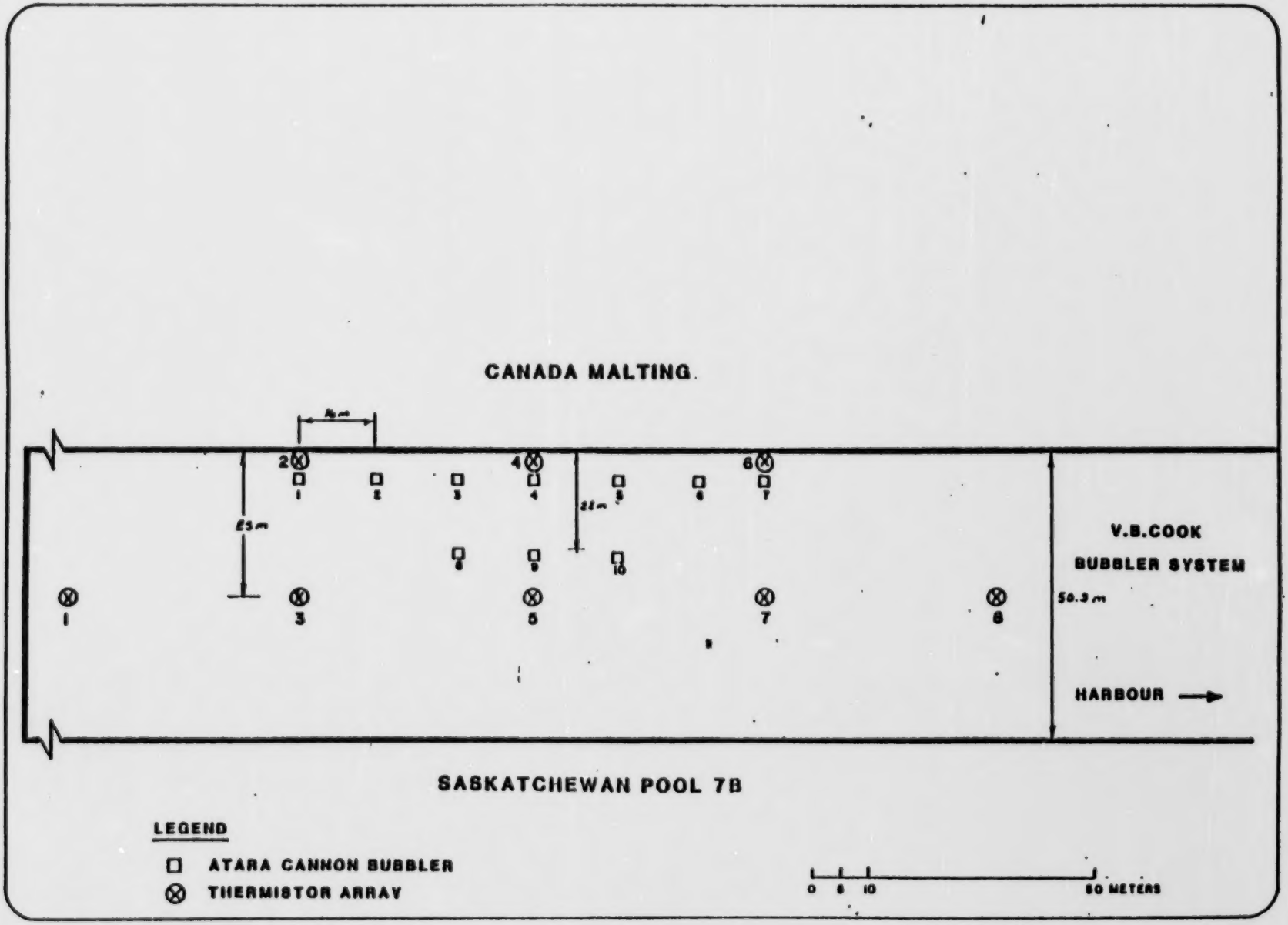


Figure 2.14 Installation at Canada Malting Slip

a) Operational Observations

- Ice thickness: control ice thickness measurements indicated that there was no natural thinning of the ice cover during the measurement period. The mean ice thickness was 65 cm. The ice melting rate, determined by measuring the change in open water areas on air photographs, was, therefore, wholly attributable to the bubbler operation.

- Air cannons with deflectors: the deflectors on the air cannons encouraged a horizontal flow of water. This was evidenced by the absence of vertical faces on the perimeter of the holes (see Figure 2.15), the thinning of ice two metres distant from the edge of the bubbler holes, as well as temperature increases measured 48 m from the nearest bubbler. The air cannons were trouble free over the operational period.

- Slip water temperature: the thermistor array and data acquisition system permitted a study of the effect of bubbling on the water temperature and circulation in the slip. Observations showed a warming trend in the upper layer of the slip once bubbling commenced (see Figure 2.16).

- System comparison: researchers used aerial photographs (see Figures 2.17 and 2.18) to determine the rate of ice melting of the three systems. Figure 2.19 illustrates the comparison.

2.5.4 Rake Bubbler System (See Figure 2.20)

The system used three of the rakes (see Figure 2.21) that had been used in the 1982/83 tests. A 40 hp Grimmer Schmidt air compressor was used with a rated capacity of 300 m^3/hr at a rated pressure of 690 kPa. The compressor, receiver and air-metering station were protected from the elements by a plywood shed. A 33-station ice metering grid was established. (See Figure 2.22) The rakes were installed on lines A, B and C at station 0 + 00 and pulled towards station 2 + 00 by small winches. Researchers applied the Ashton method to develop a model for predicting rake performance.

a) Operational Observations

- Ice thickness: the average ice thickness on line A was 58.8 cm, on line B 66.3 cm and on line C 71.4 cm. The ice deterioration was determined from both aerial photographs and from the attrition rate of the expendable stakes of the grid.

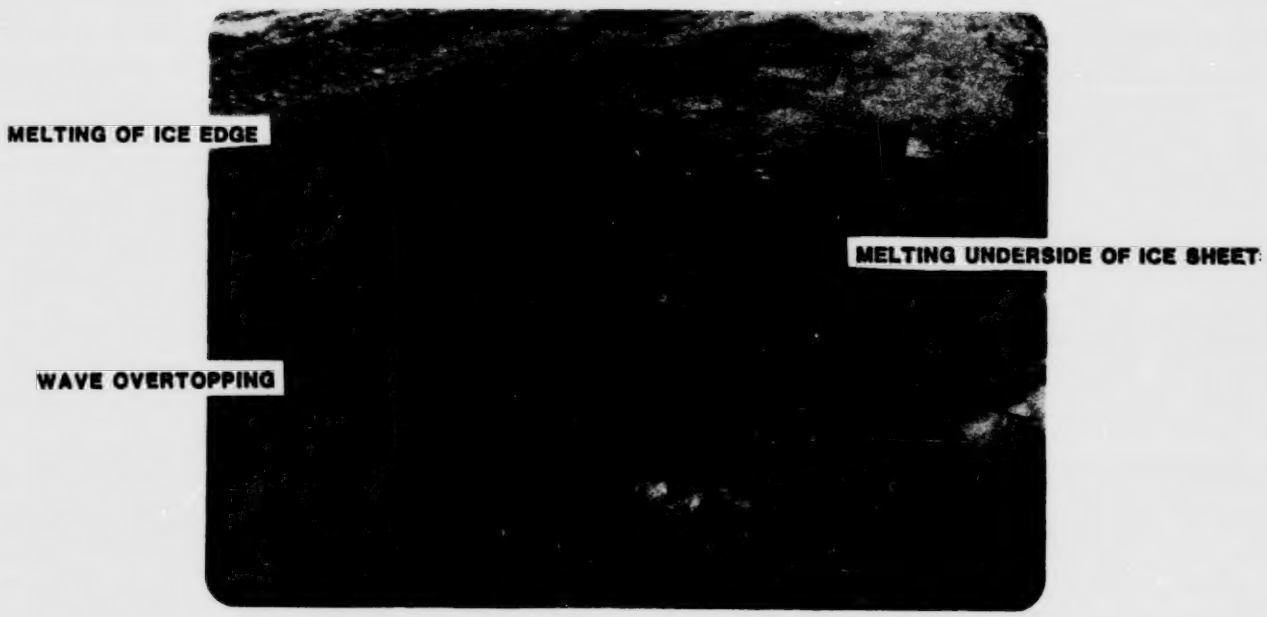


Figure 2.15 Bubbler Hole, March 10, 1984

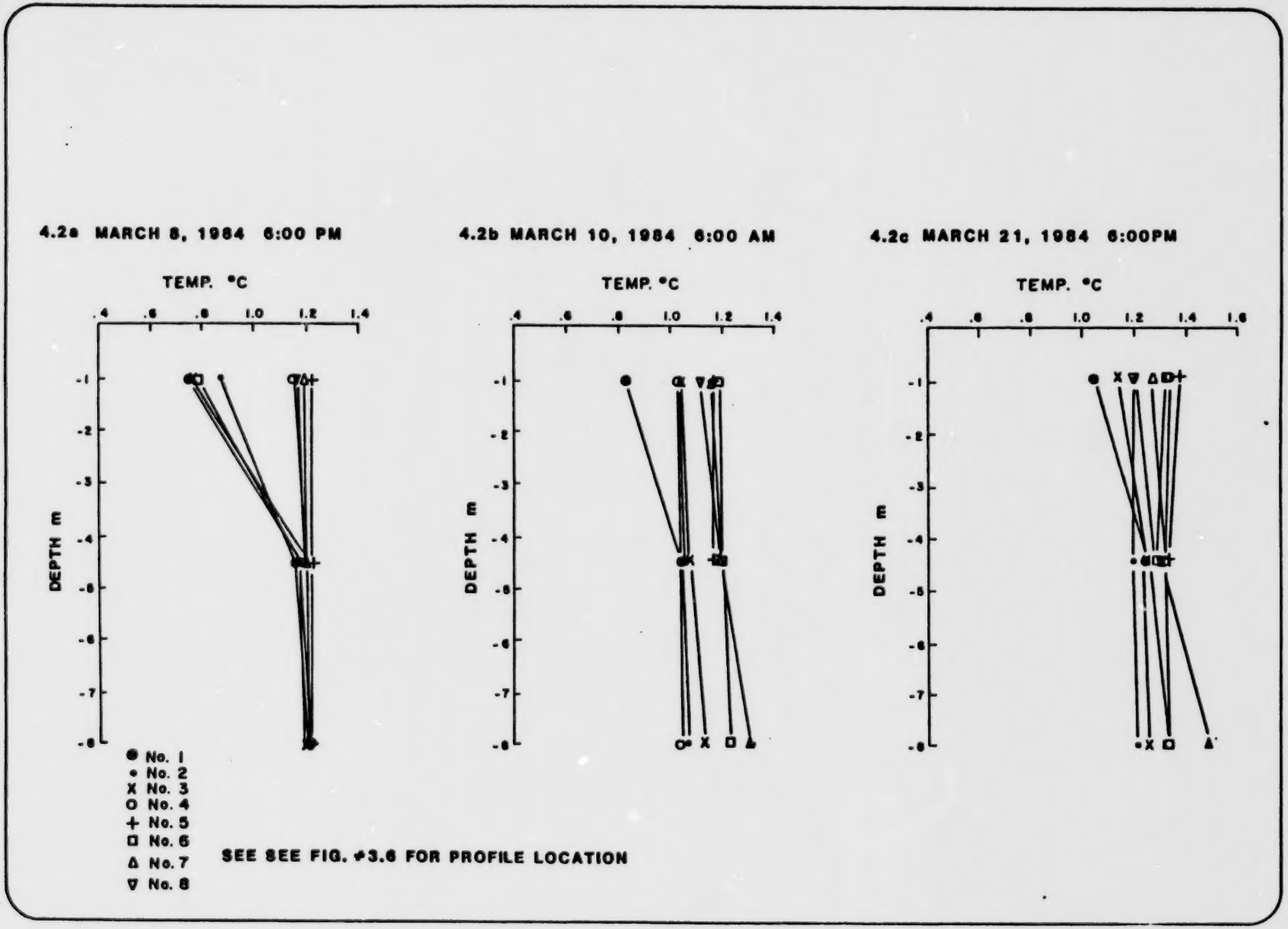


Figure 2.16 Water Temperature Profiles

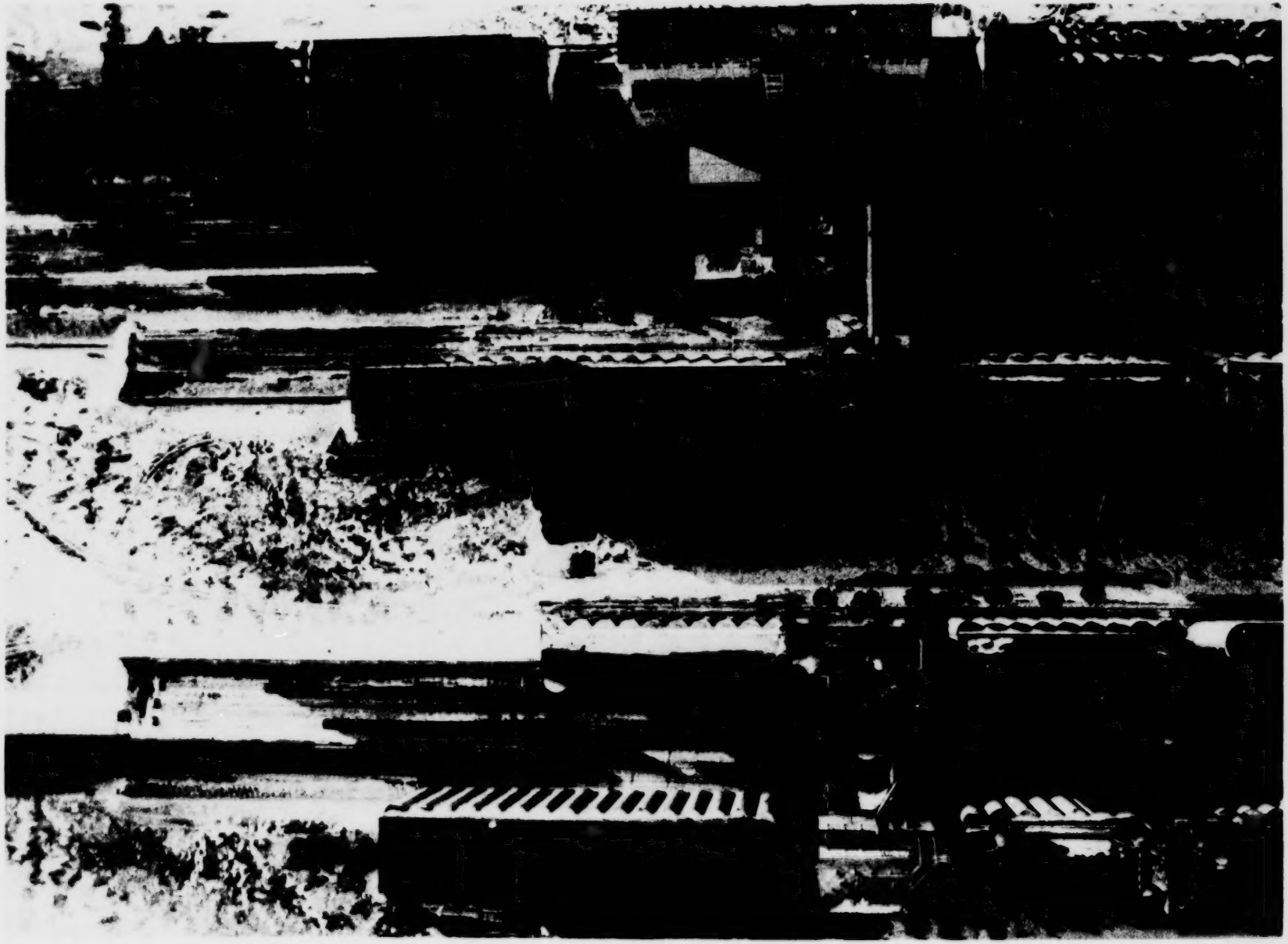


Figure 2.17 Aerial Photograph March 12, 1984

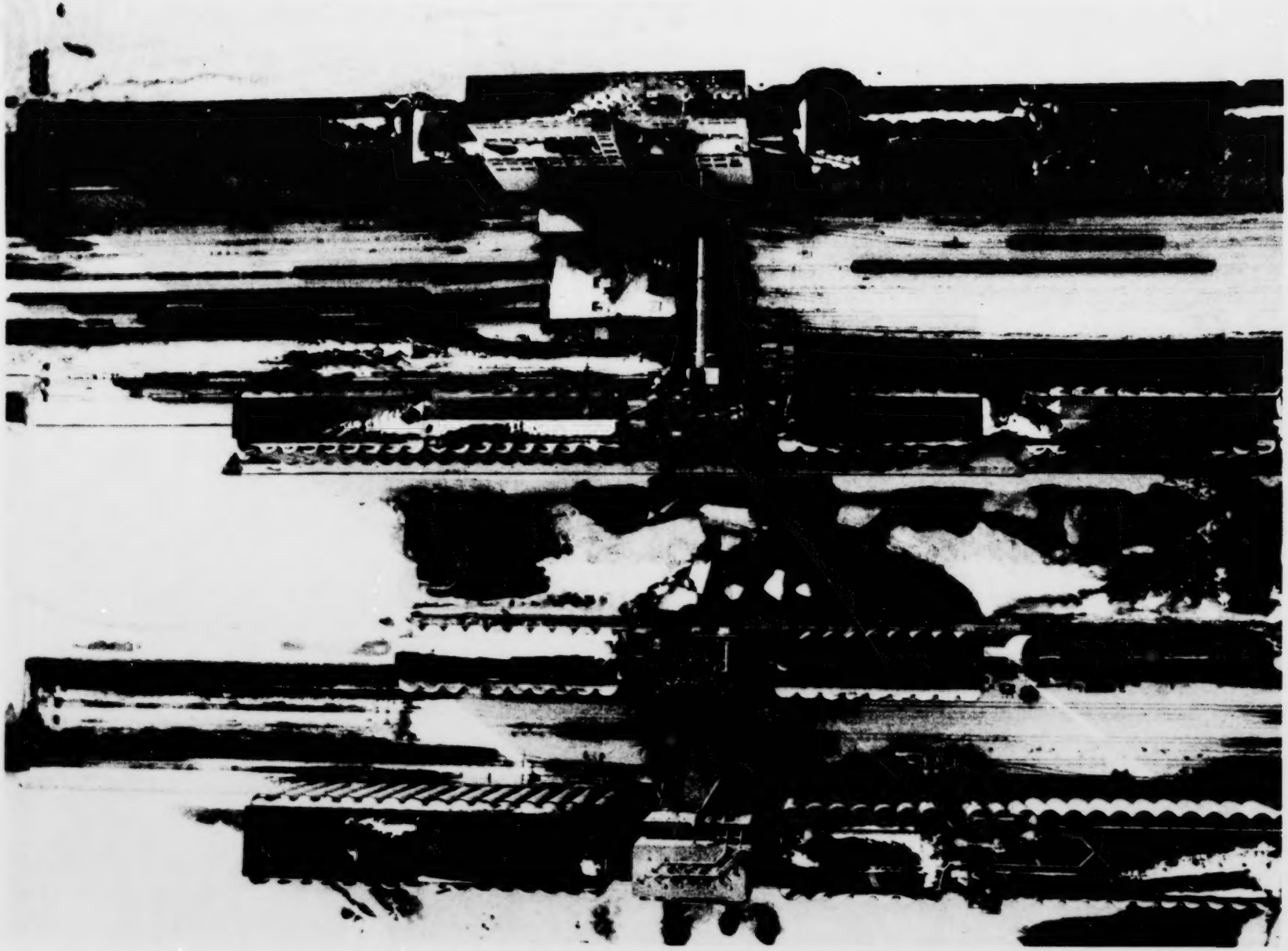


Figure 2.18 Aerial Photograph March 21, 1984

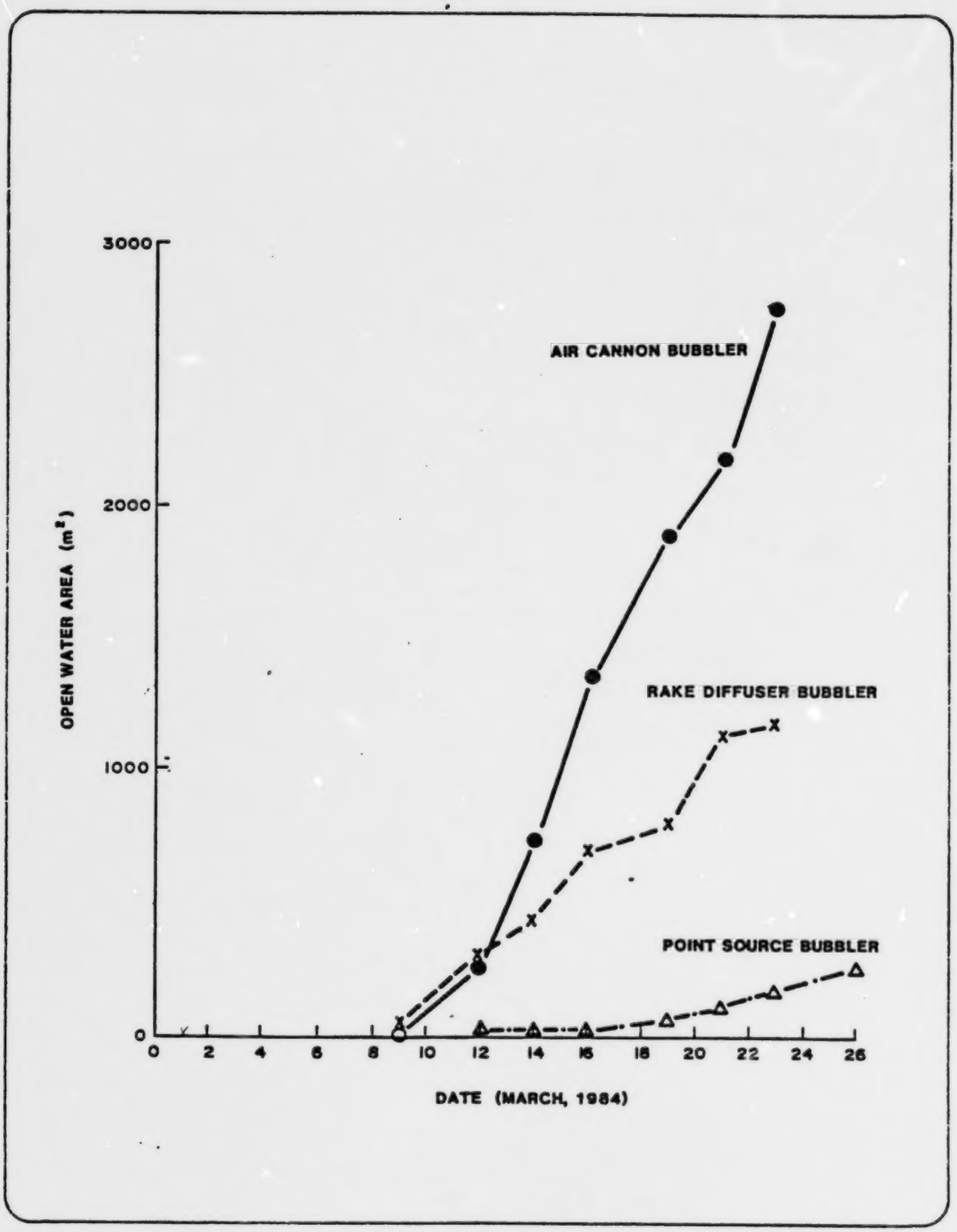


Figure 2.19 Area Melted by the De-icing Systems

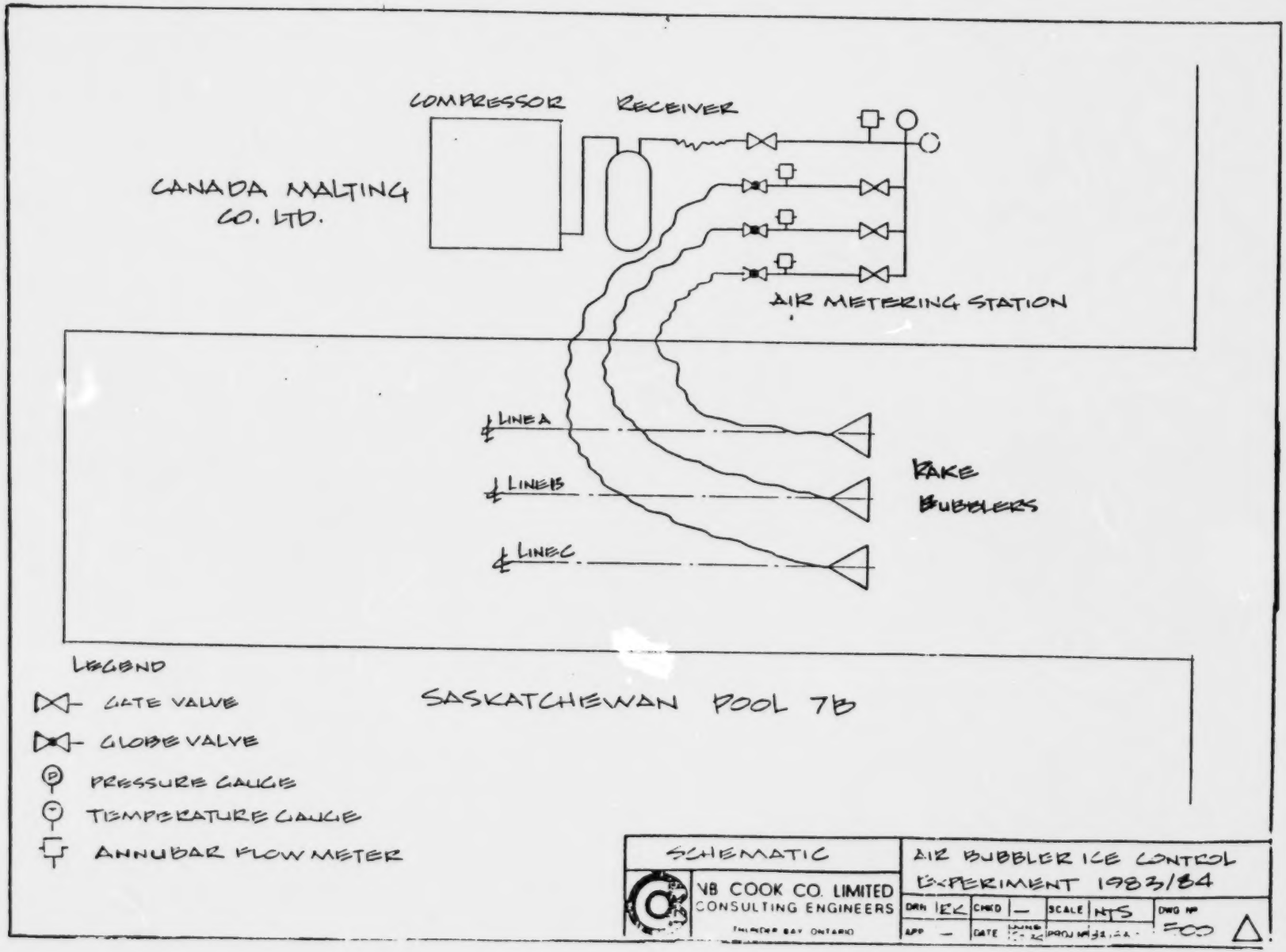


Figure 2.20 Rake Bubbler System

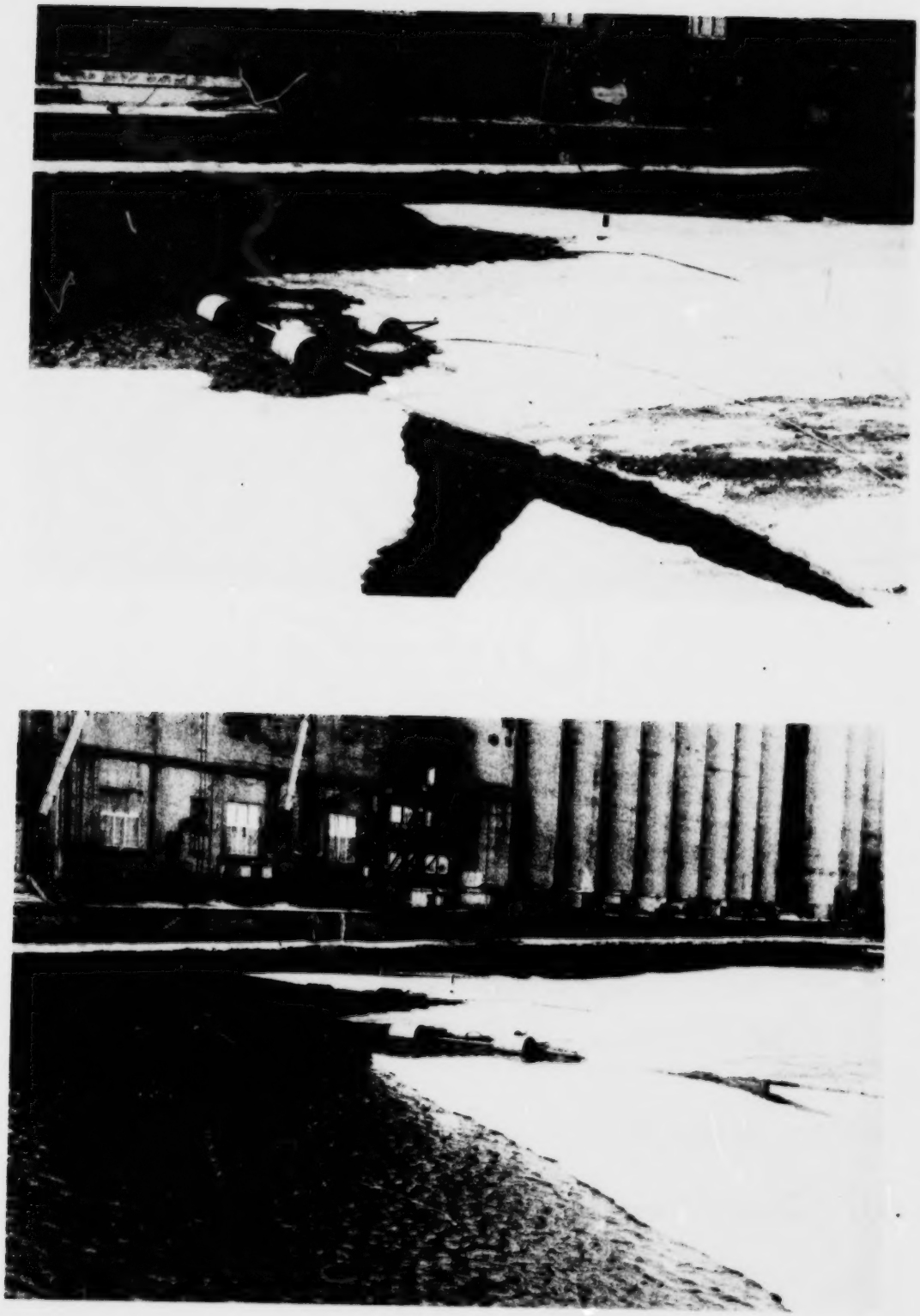


Figure 2.21 Rake Bubblers

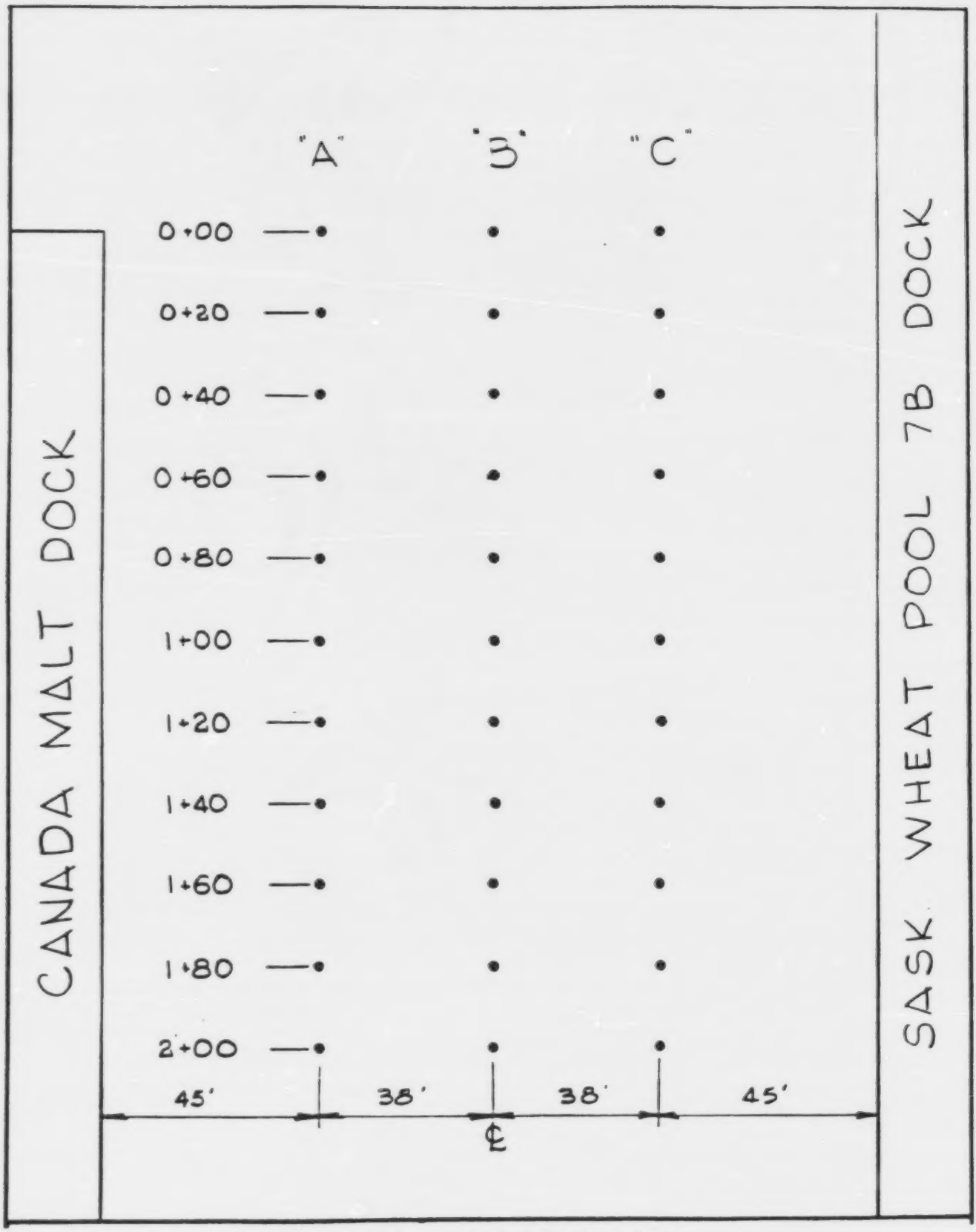


Figure 2.22 Ice Metering Grid

- "Rake" system operation: there were few operational difficulties with the rake system. Some fluctuation was experienced at the air metering stations due to the compressor loading and unloading. The rakes erode the ice most effectively when they are positioned at the brow of the ice. This was done only every day or two, hence the melting rate varies. (See Figure 2.19)
- Modelling of system: the computer model established to predict the rake performance proved to have an accuracy of approximately 7%.

2.5.5 Comment

The season's tests indicate that both the rakes and air cannons have good potential for use where line bubblers would be at risk due to ship operations. The choice of one or the other would depend not only on cost but also on the particular ice melt parameters required.

The reporting following the 1984 season included some basic cost comparisons for bubbler systems. These comparisons are necessarily crude and include prototype development costs which would not be expected in an operational system. Also the operating conditions for each system are not identical. Given these limitations Tables 2.2 and 2.3 present a best estimate to date of system costs.

An important part of the 1984 work was the information gained relating to the thermal reserve of the slip. The thermal reserve was estimated using measured temperature profiles to evaluate its effect on ice suppression. Calculations determined that the thermal reserve alone was sufficient to melt about 17% of the ice cover. Figure 2.23 shows that the heat content of the slip after March 13th was insufficient to explain the melting that actually took place. Heat is obviously added to the slip from some natural source prior to the ice break-up hence the capability for ice suppression at Thunder Bay is not limited by the thermal reserve of the slip.

2.6 Dock Load Experiment 1983/84 Season(8)

2.6.1 General

The Canadian Coast Guard Icebreaker ALEXANDER HENRY has been used to break ice in Thunder Bay Harbour outside the slips where the bubbler experiments were conducted. In recent years the use of an Air Cushion Icebreaking Bow (ACIB) notched to the ALEXANDER HENRY has greatly enhanced her ability to break ice. Arctec Canada Ltd. was contracted to measure the ice forces exerted on the grain elevator structure resulting from the movement of an icebreaking vessel within the slip.

COST ITEM	A PROTOTYPE 10-UNIT [1] AIR CANNON	B PROTOTYPE [1] RAKE	C PROTOTYPE [2] LINE
CAPITAL	$46,000	$5,400	$22,617
DEPLOYMENT	4,000	5,000	5,397
OPERATION	200		
MAINTENANCE	0		
TOTAL	$50,200	$10,400	$28,014
5-YEAR AMORTIZED ANNUAL COST	$13,400	$6,580	$9,920

[1] 1984 DOLLARS

[2] 1980 DOLLARS

Table 2.2 Cost Comparison Between Systems

SYSTEM	A PROTOTYPE 10-UNIT AIR CANNON	B 5-UNIT AIR CANNON	C PROTOTYPE RAKE	D PROTOTYPE LINE
ICE AREA CLEARED	2750 m^2	est. 1375 m^2	1100 m^2	n/a est.approx. 500 m^2
PROTOTYPE TOTAL COST	$18.25/$m^2$	$20.07/$m^2$ (est.)	$9.45/$m^2$	$56.02/$m^2$ (est.)
AMORTIZED ANNUAL COST	$4.88/$m^2$	$5.82/$m^2$	$5.98/$m^2$	$19.84/$m^2$

Table 2.3 Cost Comparison per Unit Ice Cleared

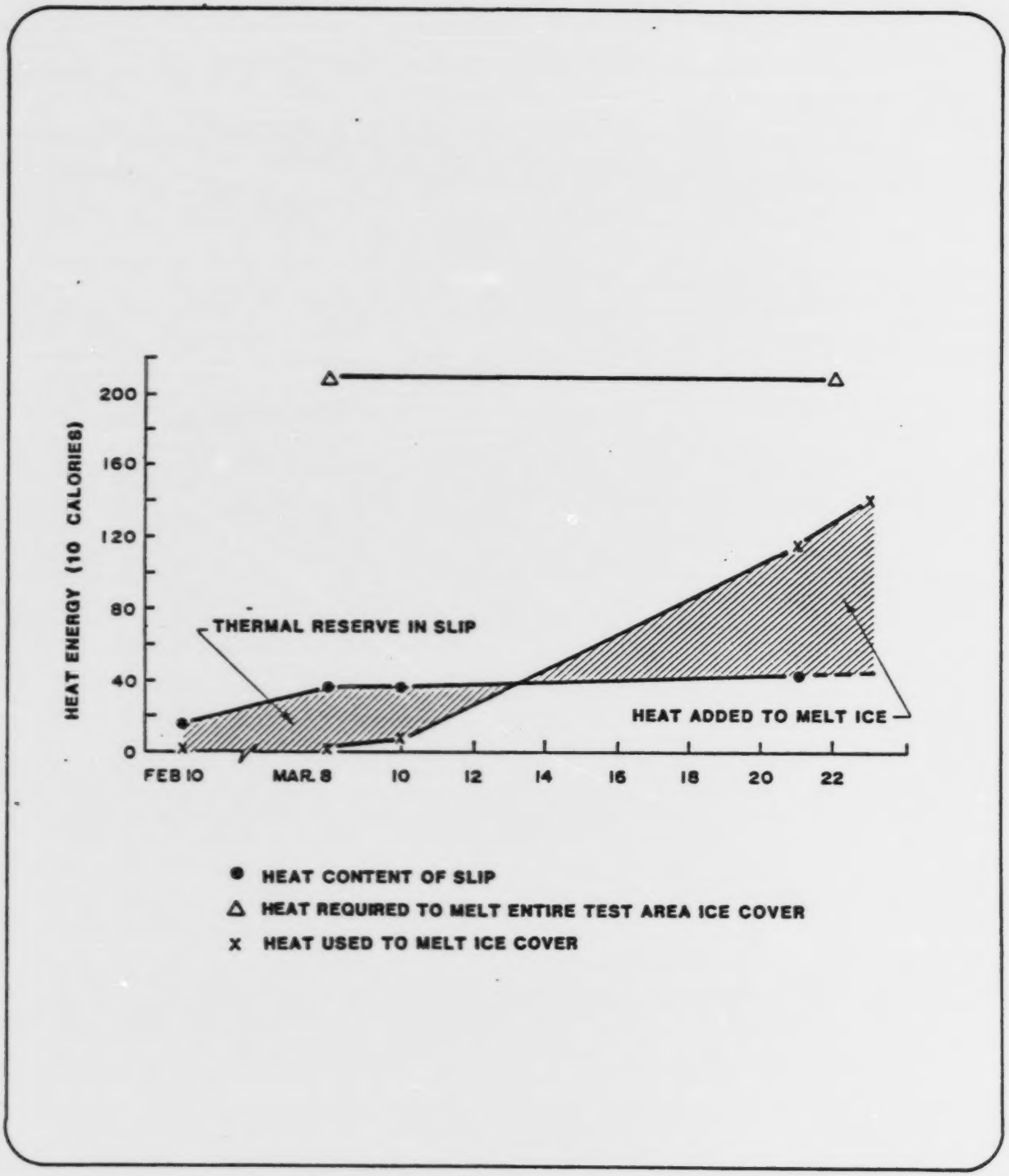


Figure 2.23 Heat Content in Slip

2.6.2 Experiment Preparations

Before the start of the tests, the dock structure and foundation were analysed to estimate a maximum safe lateral and perpendicular load that the ice could exert before causing damage. These results showed that the maximum safe load, both parallel and perpendicular to the dock face, is 365 kN/m. This maximum load is located approximately midway along the length of the dock at the Workhouse.

The estimation of forces applied to the dock during the penetration of the ALEXANDER HENRY, were calculated using a finite element model. For this computer model, conservative approximations were made. First, it was assumed that the ALEXANDER HENRY would enter the slip without the assistance of the ACIB. When the ACIB is used, the loads are considered to be lower. Second, an ice thickness of 1 m was used in the mathematical model when it was expected that the ice thickness would be less. Finally, it was assumed that the dock would be infinitely rigid, although a second scenario was used giving the dock a spring constant of 0.7 mm/kN. Predicted by the mathematical model, the maximum dock load was 87.8 kN/m for an infinitely rigid structure and 3.0 kN/m using a spring constant of 0.7 mm/kN. It was expected that the measured loads should have fallen in this range.

The estimation of the building acceleration due to the impact of the ALEXANDER HENRY with nearby ice, was performed using another finite element model. The problem was simplified by making a conservative approximation for the grain elevator. The worst case scenario used to estimate the maximum acceleration was that the ALEXANDER HENRY (or similar displacement ship) impact the corner of the dock at a speed of 5 knots. With this scenario, the maximum acceleration felt in the grain elevator would be 1.5 m/sec^2 or 0.15 g.

2.6.3 Instrumentation

The transducer locations for tests 1 and 2 are shown in Figure 2.24. The five Hexpacks (a Hexpack is an Arctec Canada designed ice pressure sensor), two averaging and three segmented, were used to measure ice pressure. They were installed by cutting a slot in the ice and freezing transducers in the positions shown. Two thermistor strings were also frozen into the ice. Each string contained three thermistors with the first thermistor approximately 0.15 m from the bottom, the second in the middle and the third approximately 0.15 m from the top of the ice. An accelerometer and video camera were used mounted at a height of approximately 35 m above the dock. The accelerometer's sensitive axis was carefully aligned to be perpendicular to the dock.

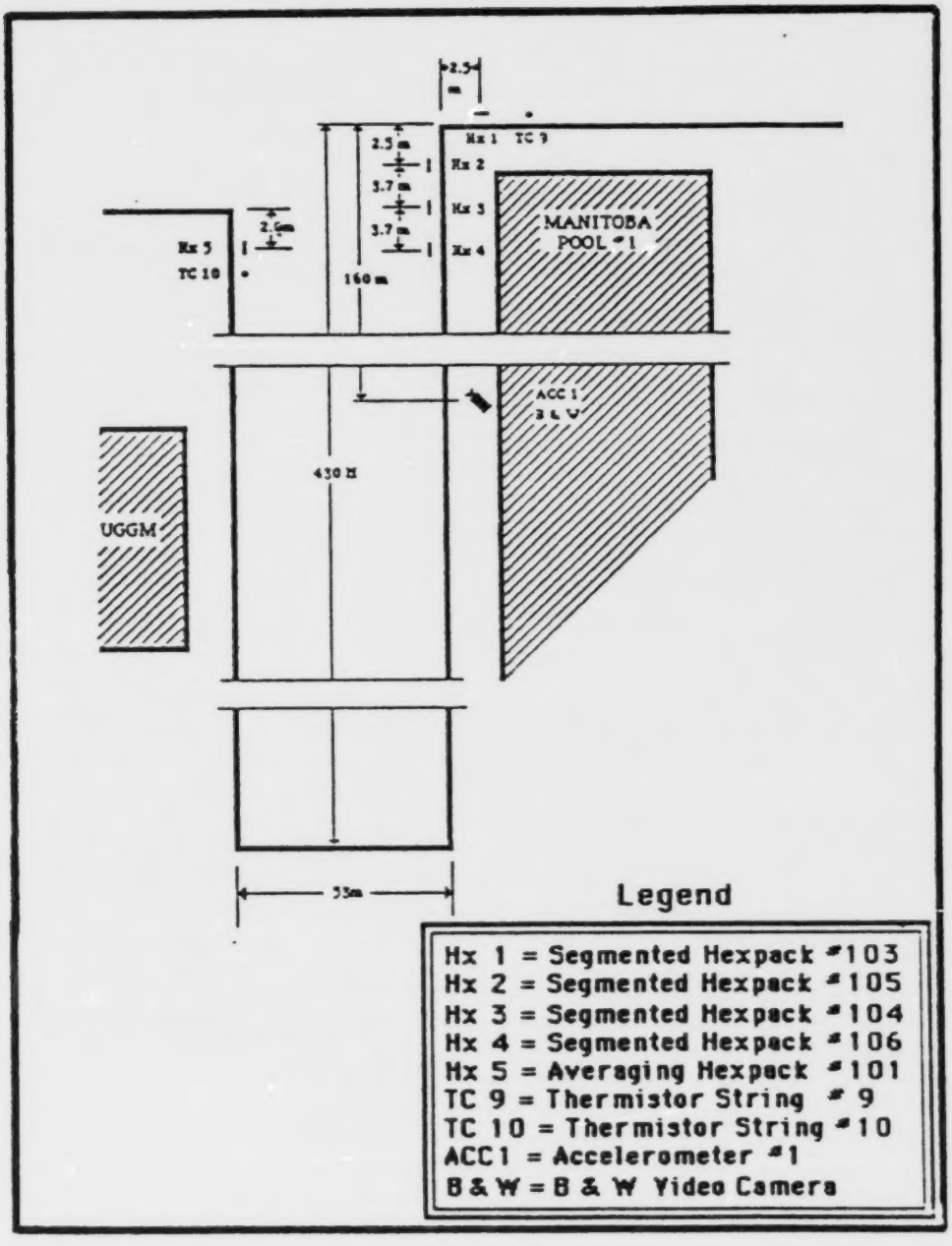


Figure 2.24 Transducer Locations for Tests 1 and 2

The data collection system used for these tests is shown in Figure 2.25. The fourteen Hexpack channels were conditioned with two series 2110, Vishay strain gauge conditioners. The accelerometer and Hexpack signals were recorded in parallel in both digital and analogue form.

The transducers for test 3 were distributed along the full length of the slip. Apart from the relocation of the Hexpacks, the addition of another accelerometer on the UGGM elevator and the removal of one thermister string, the data collection system is identical.

2.6.4 Test Program

The ALEXANDER HENRY icebreaker, with and without the ACIB system, was used for the tests. This vessel alone has a conventional bow that does not promote the downward breaking of ice, but rather tends to break the ice by crushing and splitting. The use of the ACIB notched to her bow generates considerably less horizontal force due to the different mode of icebreaking.

The analyses of the test results were made using an arbitrarily defined zero. Since thermal changes cause a considerable ice load, an absolute zero was not known. For all tests the arbitrarily selected zero was taken five to ten minutes before the tests started. All tests were run as early as possible in the morning when thermal ice loads are lower.

The first test was carried out using the ALEXANDER HENRY alone. The icebreaker approached the slip by ramming in about 0.7 m thick ice. The pressure increased continuously and the test was aborted when the icebreaker was about 50 m from the entrance of the slip. Figure 2.26 shows an analysis of the dock load distribution shortly after the ALEXANDER HENRY started her run and when the test was aborted. A peak load of 183.49 kN/m was calculated.

The second test was carried out after coupling the ACIB to the ALEXANDER HENRY. The measured ice pressures were lower and the test continued until approximately 20 m of ice in the slip was broken. At this point the ACIB was in a light condition, the cushion pressure was sufficient for breaking ice in the bay but not set for the ice conditions in the slip. The test was aborted when the ACIB was unable to break the thick ice in the slip. Figure 2.27 shows a typical example of the dock load distribution at the start of the test using the ALEXANDER HENRY/ACIB combination. A maximum load of 125 kN/m was calculated.

The third test was carried out three days later using the ALEXANDER HENRY/ACIB combination. The ACIB was ballasted to a 90 cm water column pressure, the pressure needed to cope

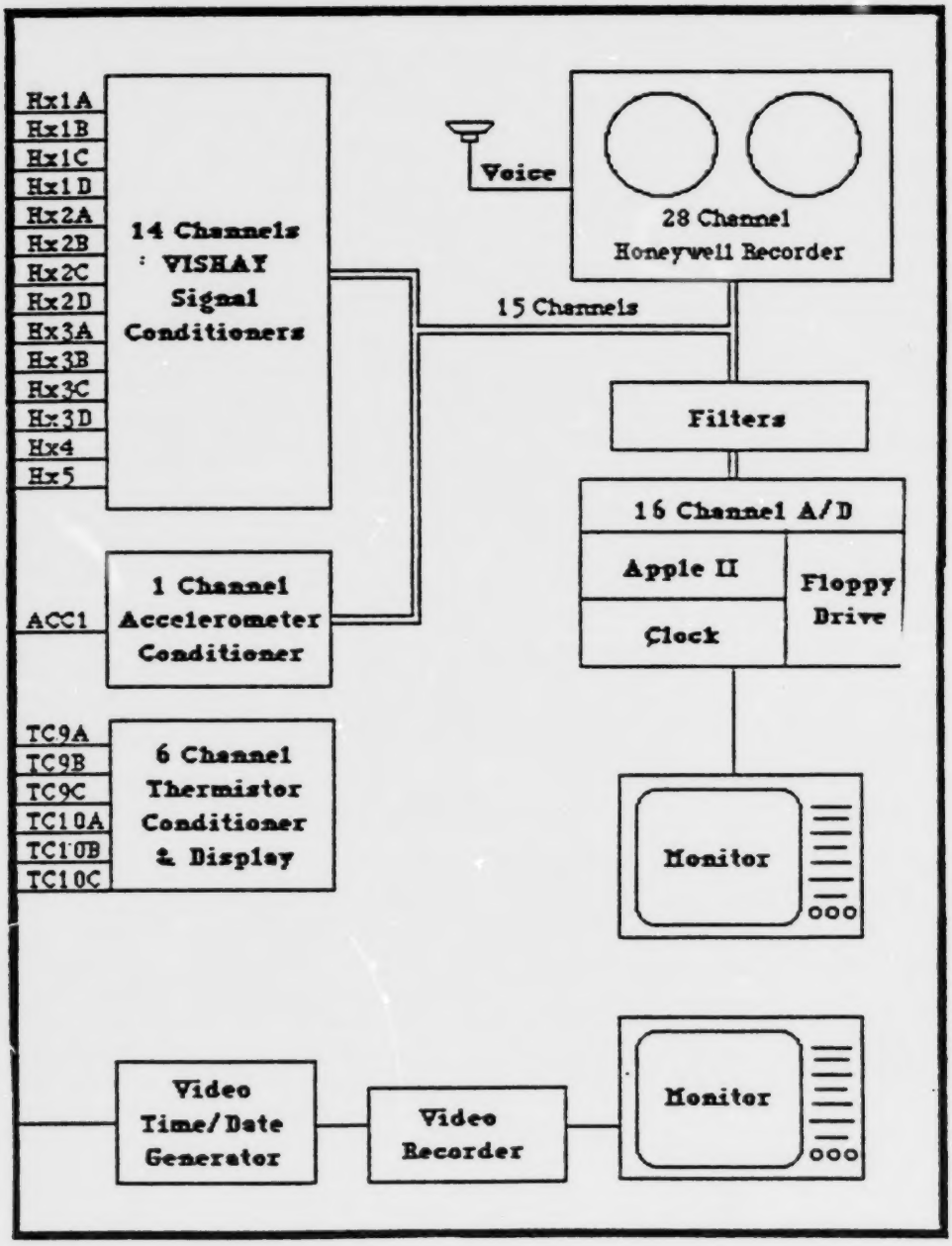


Figure 2.25 Data Collection System

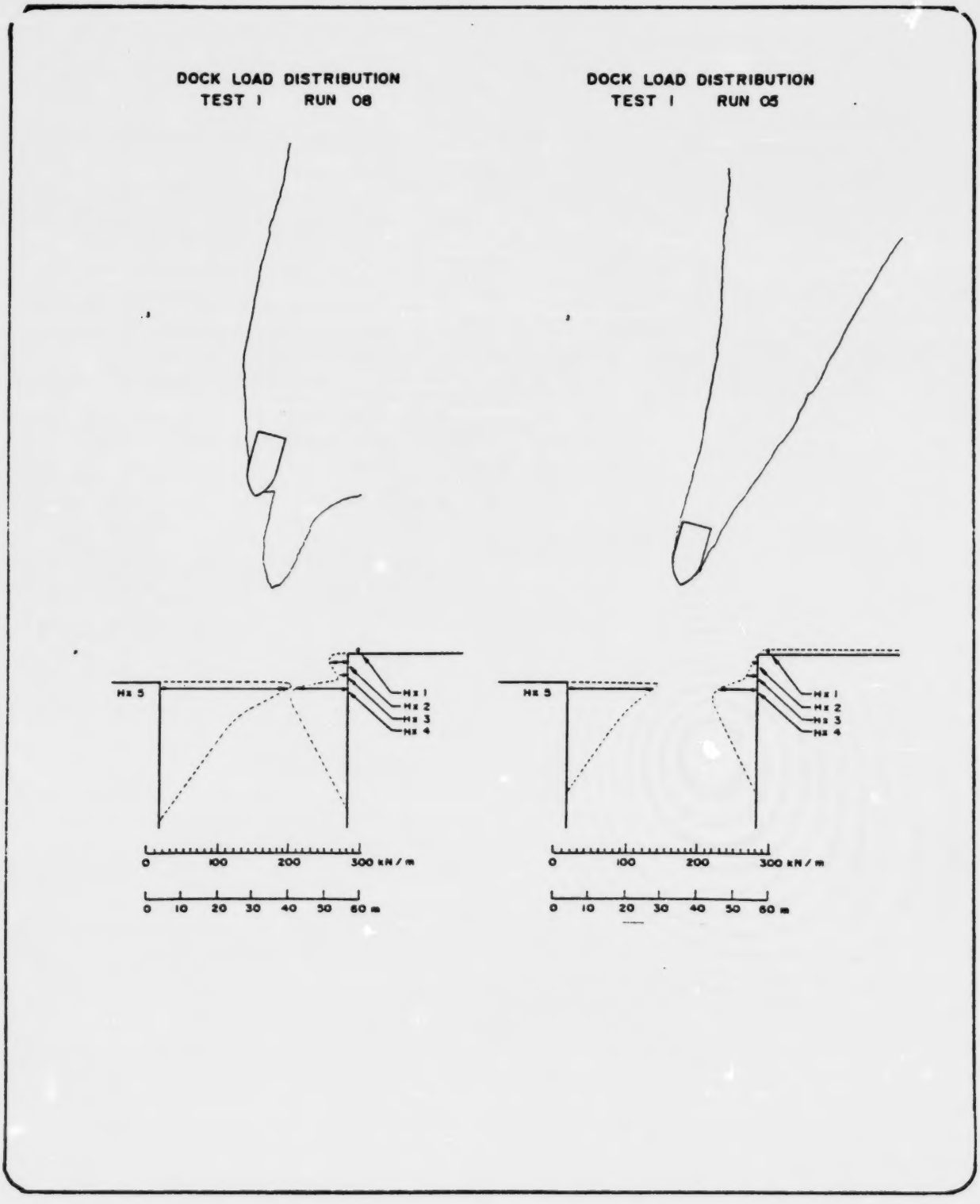


Figure 2.26 Dock Load Distribution - Test 1

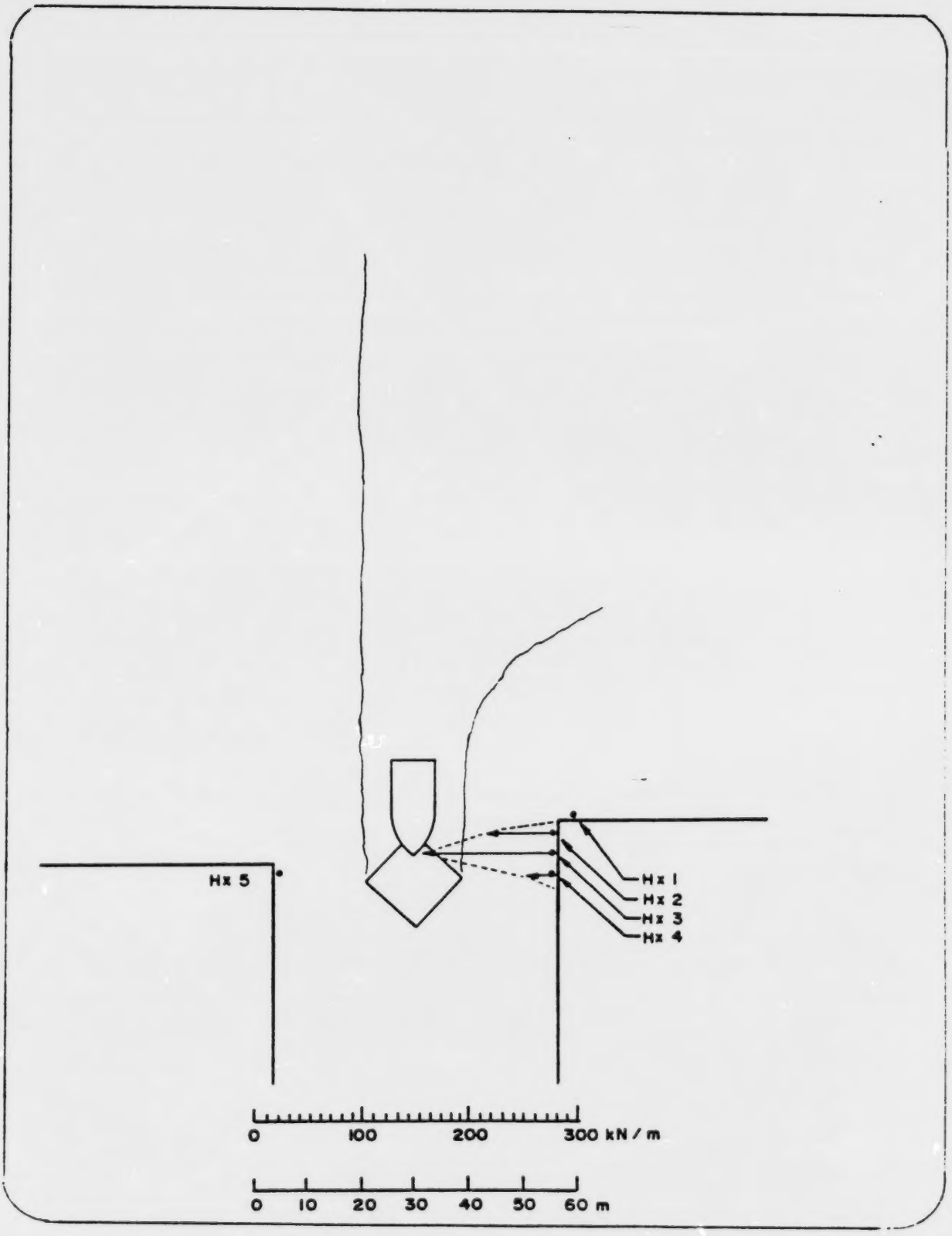


Figure 2.27 Dock Load Distribution - Test 2

with the ice in the slip. For this test the Hexpack pressure transducers were relocated along a longer length of the slip. Figure 2.28 summarizes the ice loads measured during test 3. The three highest loads measured were 178.1, 143.9 and 121.8 kN/m.

- Thermal loads: the ice pressures due to thermal stresses were measured over a 36-hour period. During this time both air and ice temperatures were recorded. The temperature at the top of the ice ranged between -3.9°C and -0.1°C, while the temperature at the bottom ranged between -1.7°C and 0.2°C. This temperature fluctuation, as well as the temperature differential through the ice thickness, produce thermal stresses which were recorded by the Hexpacks.The maximum pressure fluctuation recorded due to thermal effects varied between +50 kPa and -275 kPa. This ice pressure translates into a dock load ranging between +100 kN/m to -300 kN/m during a relatively mild variation of air temperature.

2.6.5 Comment

The maximum allowable force along the full length of the dock was calculated to be 365 kN/m. The force due to thermal expansion alone was measured at 300 kN/m, therefore, great care must be taken when introducing ice breaking ships into a slip to break ice.

Great care should be exercised if conventional ice breakers are to be used for breaking ice in a slip. On the other hand, the ACIB proved effective without endangering the structure. There might be other vessels with advanced bows that break ice with a sufficiently low horizontal force component that could also be used.

The analytical approach used plus the field measurements proved to be an appropriate method of evaluating pressures applied on structures located around navigation channels.

2.7 Air Bubbler Installation Performance Monitoring Spring 1985 (7)

2.7.1 General

In 1984 renovations were carried out on a 95 m length of the Saskatchewan Wheat Pool slip wall. This work provided an opportunity to install a permanent bubbler system in the outshore slip wall. The system layout and bubbler unit detail is given in Figures 2.29 and 2.30.

The system was monitored during its operation in 1985 to provide the answers to four questions:

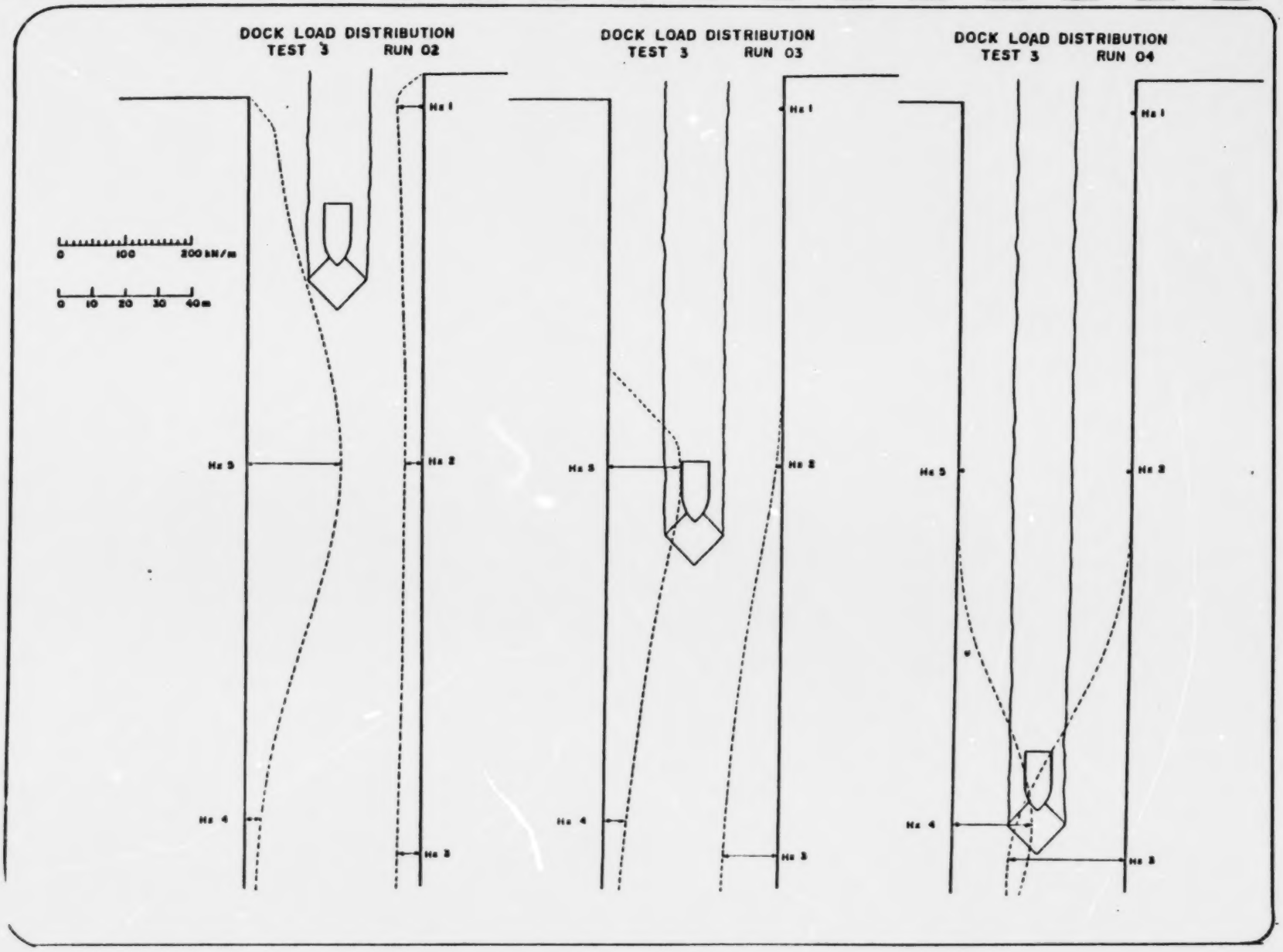


Figure 2.28 Dock Load Distribution - Test 3

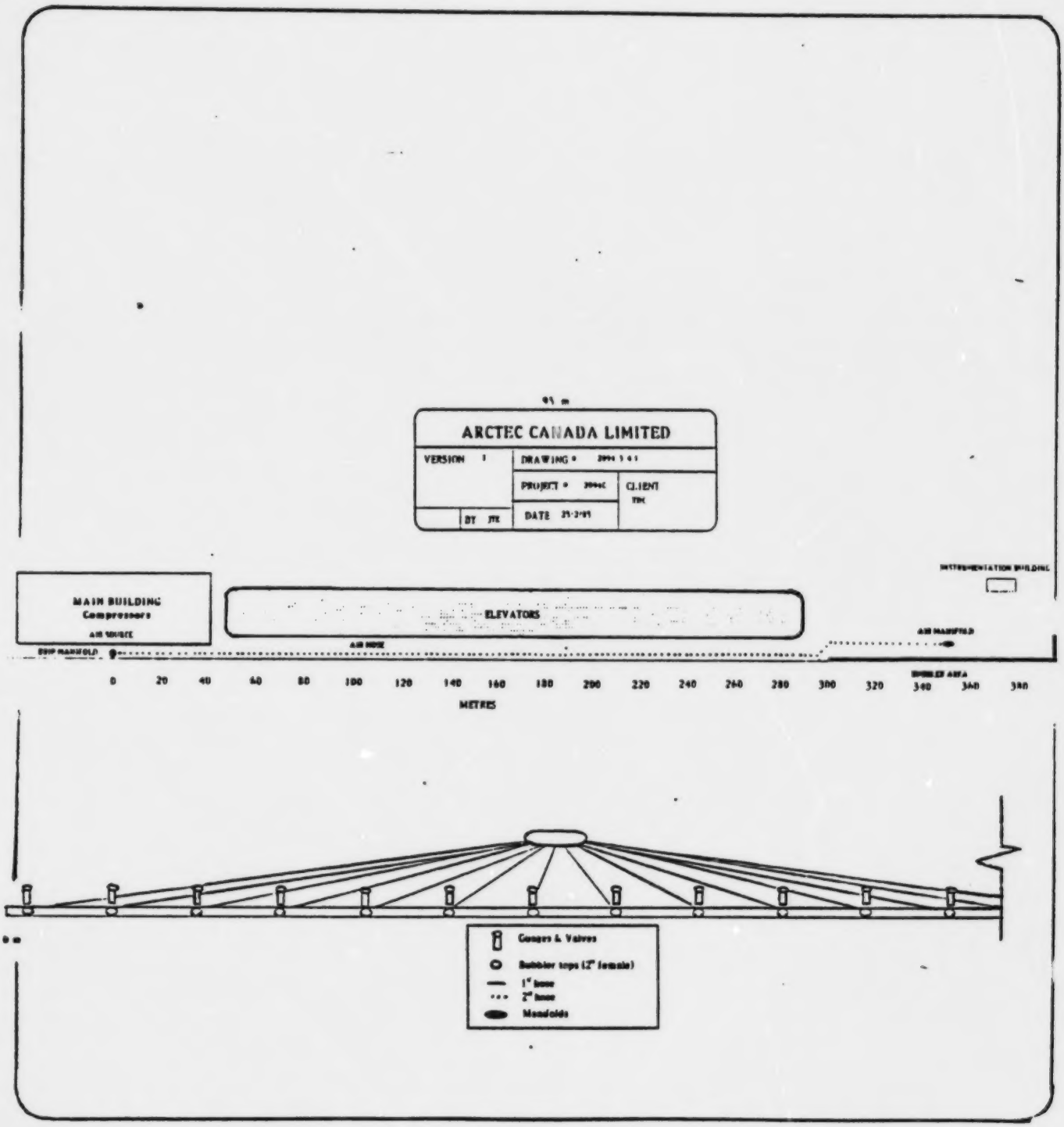


Figure 2.29 Air Bubbler System in Saskatchewan Wheat Pool Slip

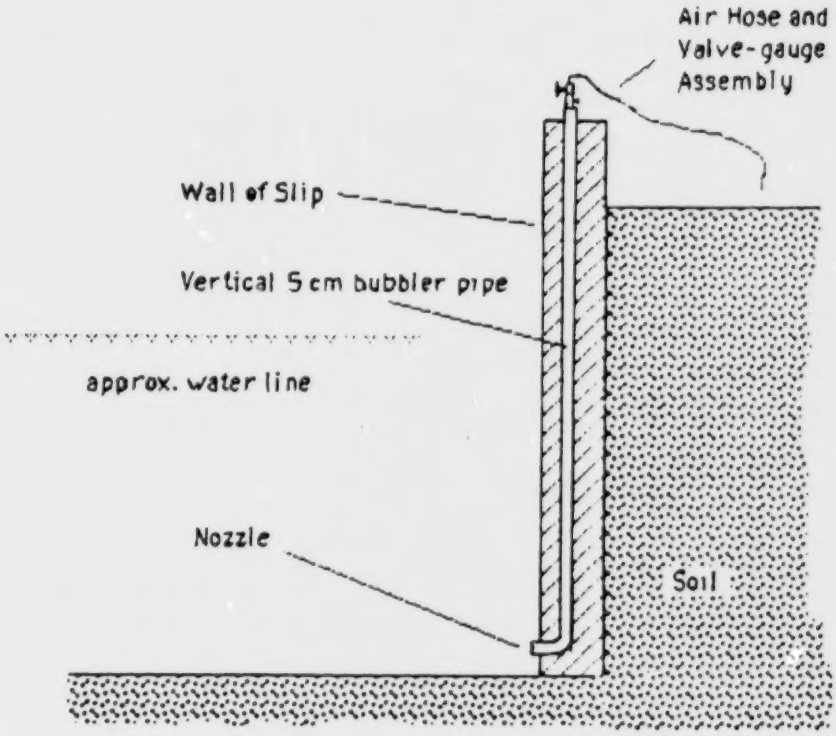


Figure 2.30 Bubbler Unit Detail

- how effective is the system in moving deep warmer water to the ice?

- what rate of ice melting was initiated by the system?

- what is the source of the melting effect?

- what is the cost/unit of ice melted?

2.7.2 Monitoring systems

a) Temperature Monitoring

The temperature monitoring system consisted of 28 thermistors to sense temperature, a multiplexing scanner and a controlling computer/data storage package.

The thermistors were deployed throughout the slip as shown in Figure 2.31. The data acquisition system is illustrated in Figure 2.32.

Monitoring was conducted during two separate intervals, one from February 8th through March 12th, 1985 prior to bubbler operations; the other from March 12th until March 16th covering the period the bubbler was initially operational.

b) Air Pressure Monitoring

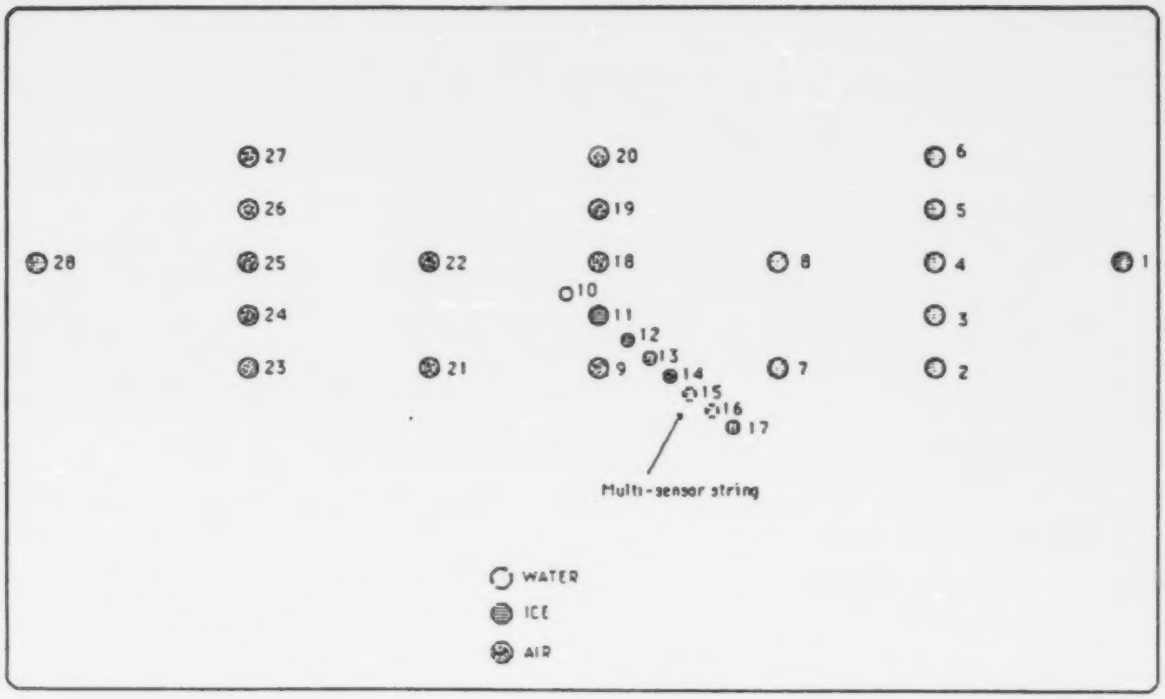
The air pressure readings were taken at the top of each vertical bubbler pipe using standard compressed air gauges.

2.7.3 Operational Observations

- Air temperatures: the air temperature varied from 7.8°C to -26.4°C.

- Water Temperatures: spatial water temperature patterns described by temperature isolines were plotted both before and after the bubbler started to operate. Figure 2.33 is an example of the plots made. The vertical gradient was also plotted. Figure 2.34 is an example of the gradient plots.

- Airflow: the air pressures measured for each bubbler unit were fairly consistant at 500 kPa ± 5%. Variations from this pressure were attributed to blockages of the bubbler nozzel. This infiltration of the nozzels with debris usually followed an interruption in the bubbler operation. These interruptions were caused when condensation from the compressed air caused icing of the hose connections along the wharf.



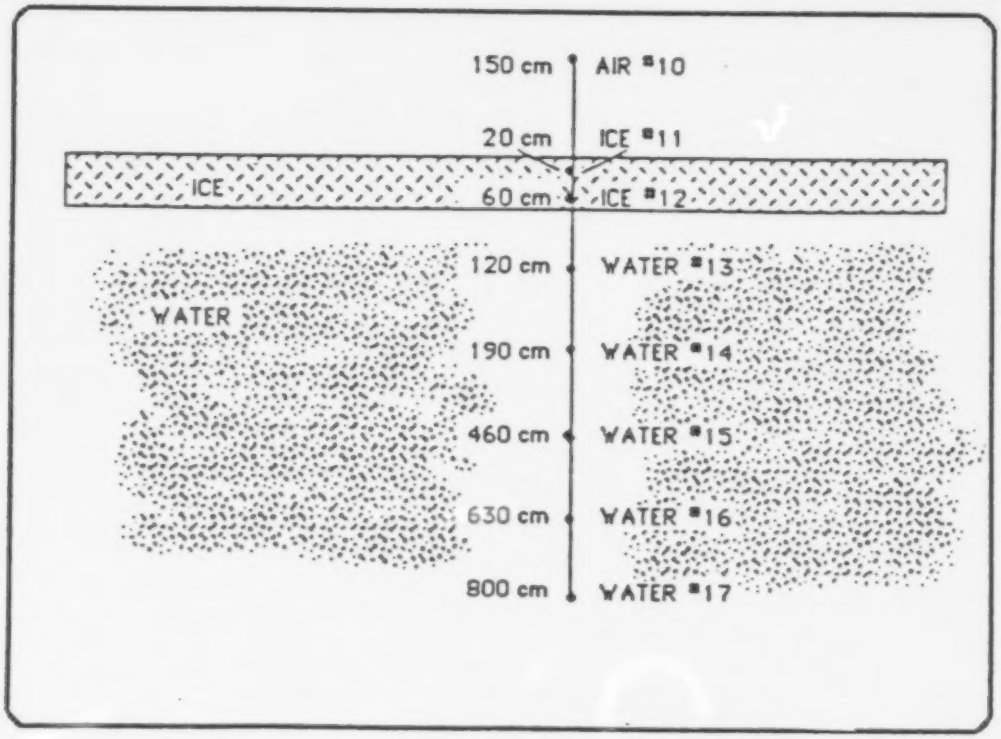


Figure 2.31 Thermistor Arrangement

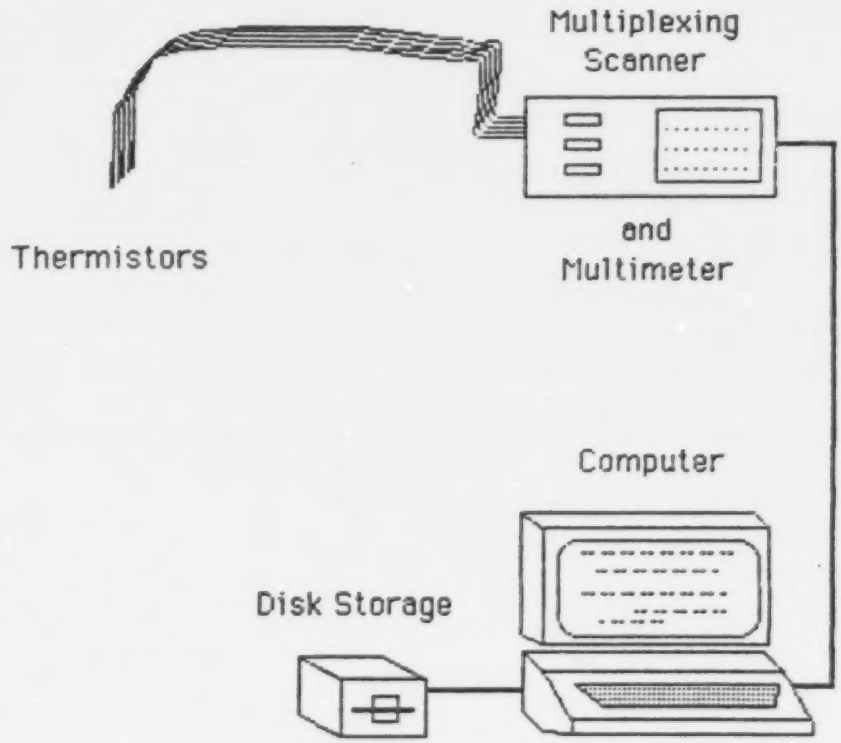


Figure 2.32 Data Acquisition System

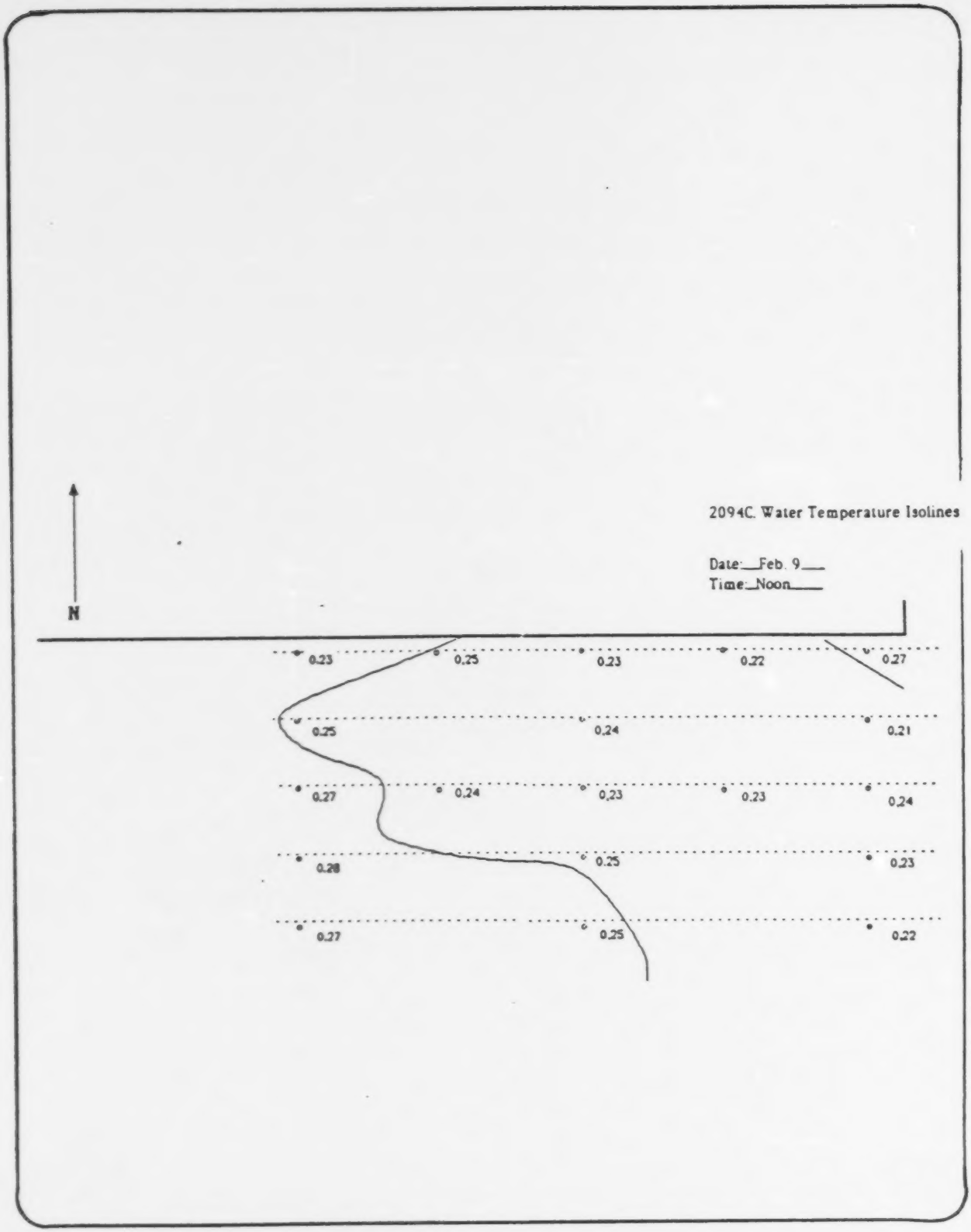


Figure 2.33 Water Temperature Isolines

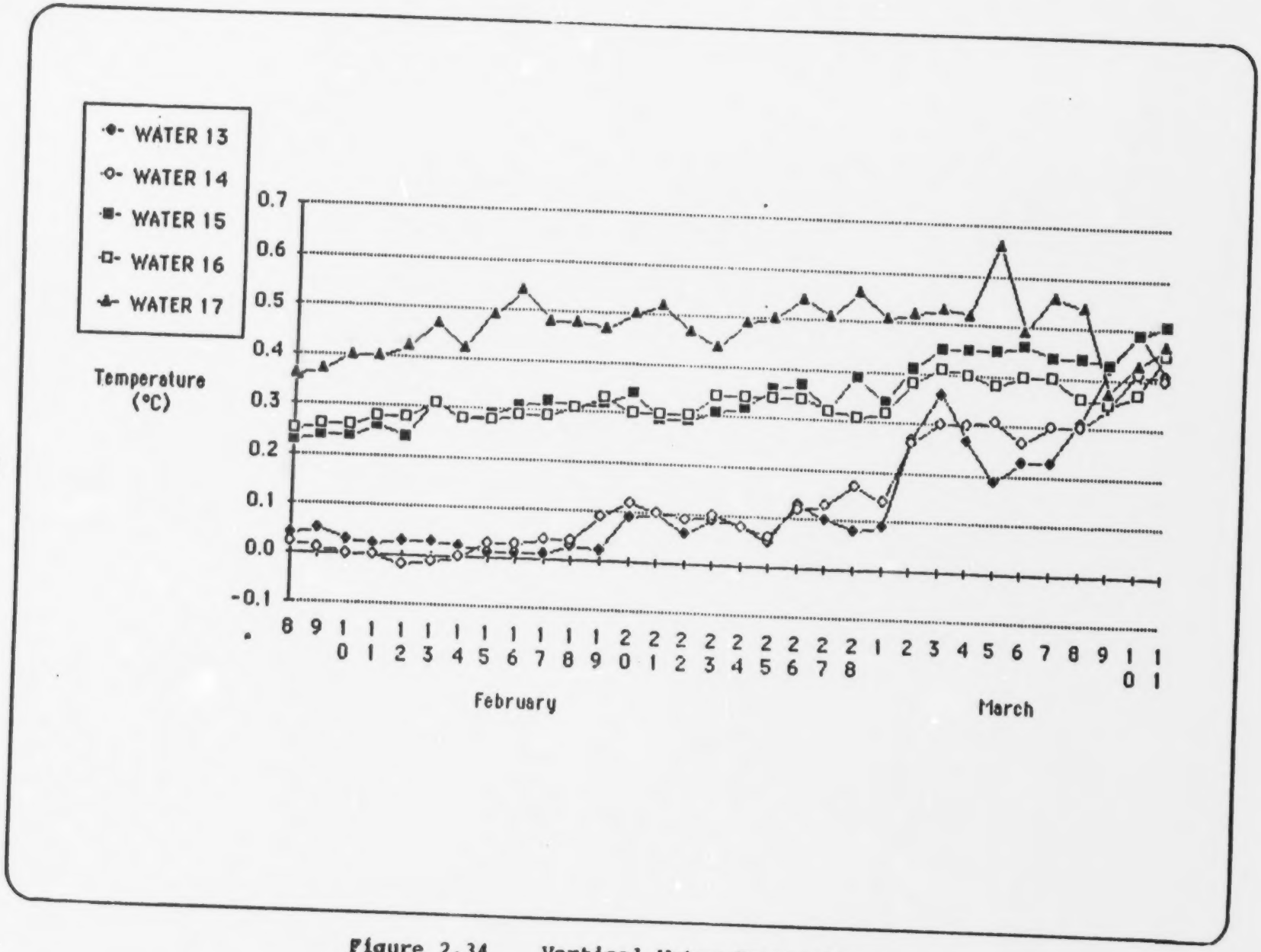


Figure 2.34 Vertical Water Temperature

- Area of ice melted: the area of ice melted was recorded by aerial photographs. The total ice melted, before icebreaker action affected the open water area, was 689.6 m^2. Figure 2.35 plots the ice melt.

- Ice thickness: the ice thickness was measured at each thermistor location. It grew from a mean thickness of 49.8 cm in February to a mean thickness of 56.1 cm in March. Figure 2.36 illustrates the changes at each thermistor location.

2.7.4 Comment

a) Thermal Reserve of Slip

The extensive data acquisition system for temperature measurements permitted researchers to demonstrate that the thermal reserve of the slip actually increased during the last period. This fact had been noted in previous years as being the only explanation for the melting observed. The 1985 temperature monitoring actually measured the reserve increase. It is argued in the report that heat is gained from heat stored during the previous summer in the soil at the bottom of the slip. The argument is supported with calculations based on the standard heat transfer theories of Keith and Black. The heat transfer from the soil is enhanced by the movement of the water such as occurs during bubbler operations.

b) Ice Melting Effectiveness

The temperature profiles plotted are interpreted to demonstrate the effectiveness of the bubbler system for moving deep water vertically up to the ice/water interface. The rate of ice melt was approximately 100 m^2/day, approximately the same as the rake diffuser system tested in 1984. (See Figure 2.37)

c) System Costs

The costs for this particular installation were \$8.83/m^2 of ice melted. Estimates for the annual costs associated with a full length installation are \$4.77 m^2. This compares favourably with other systems tested.

2.8 Archimedean Screw Tractor(1)

2.8.1 Vehicle Description

The Archimedean Screw Tractor (AST) is a novel amphibious vehicle supported and propelled by contra-rotating helical screws located along its side. (See Figure 2.38)

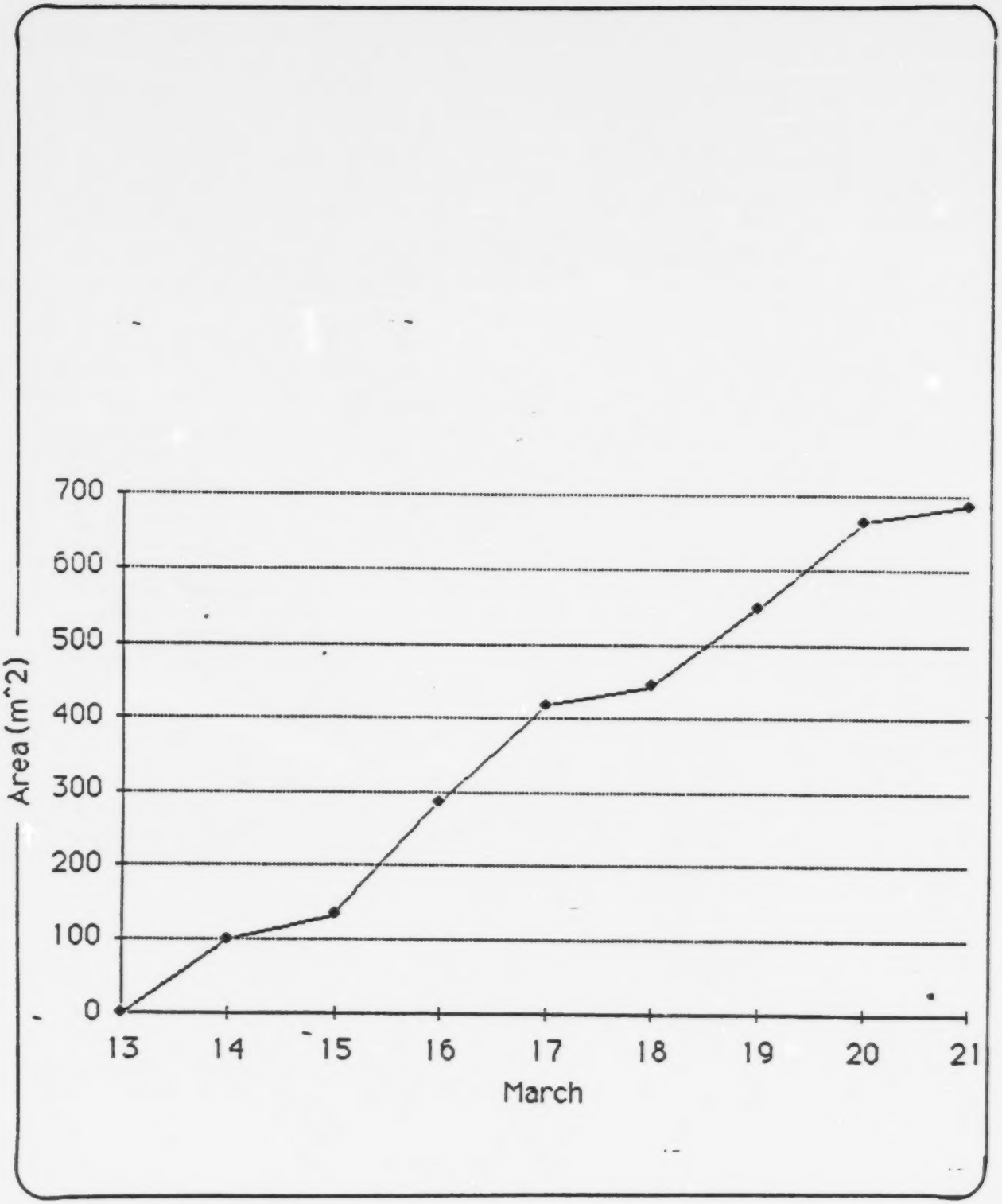


Figure 2.35 Area of Ice Melted

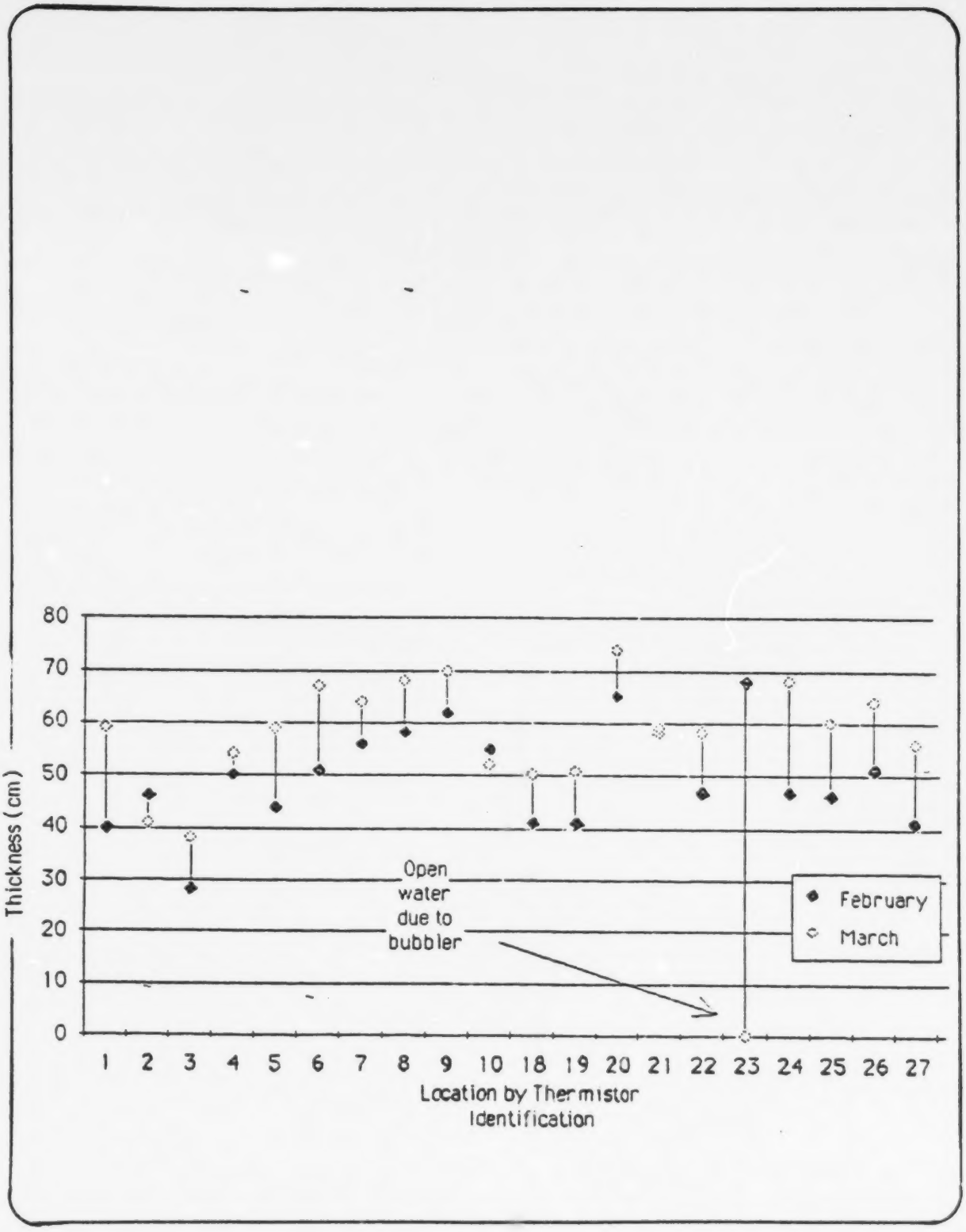


Figure 2.36 Changes in Ice Thickness

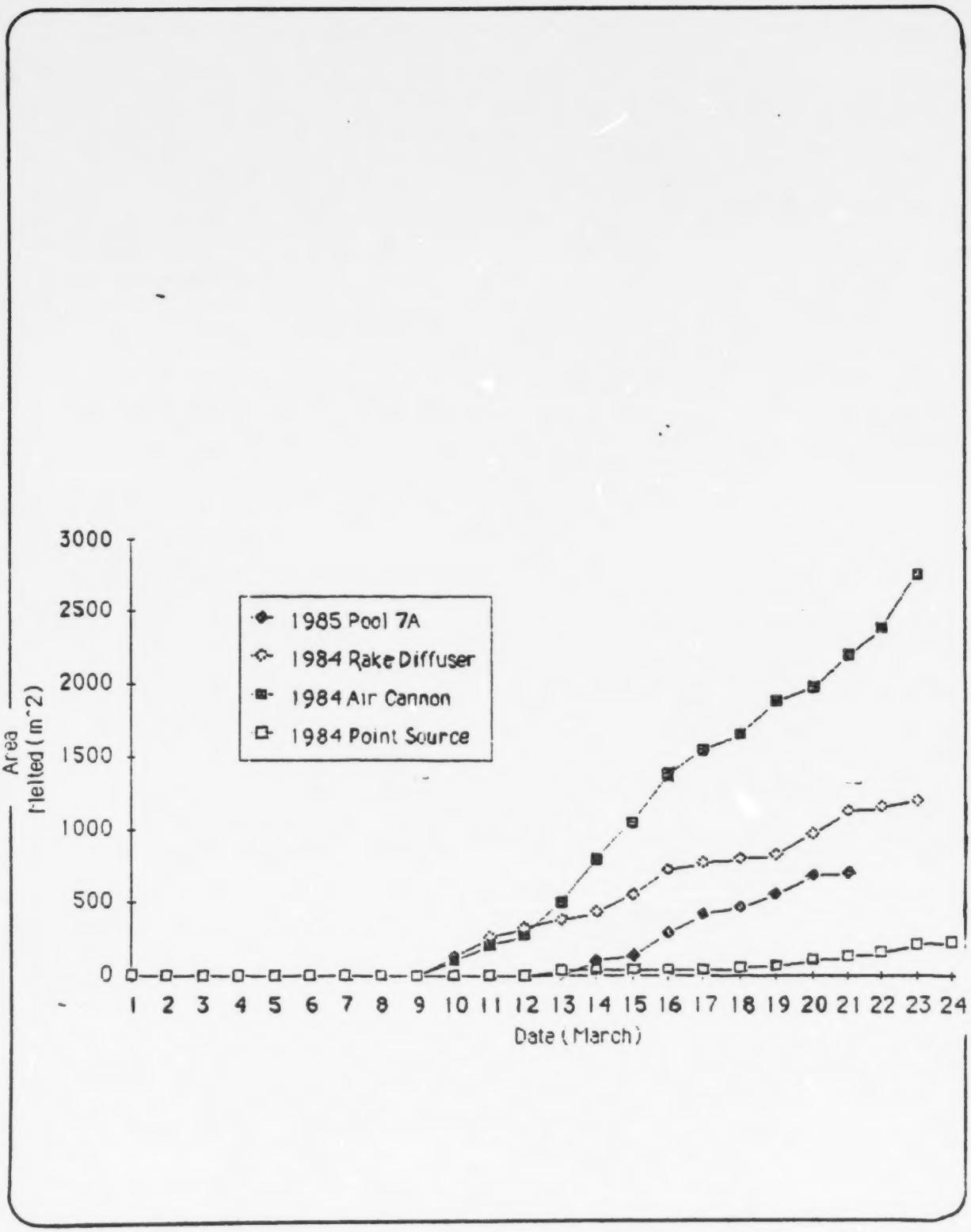


Figure 2.37 Area Melted by Four De-icing Systems

Figure 2.38 Archimedean Screw Tractor

The AST concept was suggested by Arctec Canada and designed and built in Japan by Mitsui. It is driven by an air-cooled Mitsui-Duetz V12 diesel, which operates a hydraulic generator. The hydraulics are connected to two large motors on the aft end of the rotor mounts. The motors are individually controlled. Each rotor rotation is thus separately controlled and may turn in either direction. The craft is propelled forward by contra-rotating the rotors and using the screw threads to pull itself along the surface. Similarly, the rotors are able to propel the craft in water or on snow or mud. The driver controls the rotors with two control levers which operate hydraulic valves. Turning is accomplished by slowing, stopping, or even reversing one rotor while advancing the other.

The vehicle breaks ice by applying nearly the total craft weight to the edge of an ice sheet, thereby failing the ice. If the ice is thin enough (approximately 30 cm or less) the AST will fail the ice with its weight without requiring an edge to start. By starting from open water, the AST climbs up the ice edge using the rotor threads and balances briefly on the edge when about 90% out of the water. In this way almost all of the 11 tons of the craft mass is applied to the ice edge.

The AST has a large draw bar pull on ice or snow surfaces - nearly equivalent to its own weight. In water the AST is able to pull about one ton. It is able to tow much more than its own weight on ice or snow if the load is sled mounted. Reports from some previous tests at Prudhoe Bay indicate that up to 70 tons may be pulled under good surface conditions.

A number of AST designs have been proposed for various specific uses, including Arctic barges and oil recovery vehicles. The AST concept is easily modified or redesigned for larger or more powerful craft, or for purposes requiring special accessories or functions.

The AST was used in Thunder Bay to perform a variety of tasks which tested its effectiveness as a general purpose heavy duty vehicle, a cargo carrier, a support vessel, a tractor/tug and an icebreaker.

2.8.2 Thunder Bay Experience with the AST

The AST was used to construct 16 ice management test plots which were subsequently given various surface treatments to encourage melting. During their construction the AST was used as a tractor or bulldozer giving the operators good experience in controlling the vehicle over level ice and snow.

Various icebreaking runs were made with the AST and, by combining several driving techniques, eg. rocking at edge of ice, slamming into ice, stopping on edge of ice, the AST could consistently break ice up to 0.6 m thick.

The vehicle performed well as a personnel carrier over snow, ice and previously broken ship tracks. It was highly manoeuverable and could be steered with considerable accuracy and speed (up to 3 knots) even among large ice pieces. Some padded or shock absorbing seats would add considerably to the comfort of passengers.

The draw bar pull of the AST was tested. There was no difficulty pulling loads on snow or ice surfaces provided the load is directly astern. The craft gets pulled around if tows are attempted with the load offset from the fore-aft axis by more than 10°. The AST is not able to pull a load very effectively in either water or broken ice.

2.8.3 Comment

In general the AST-002 performed well during the evaluation at Thunder Bay. The craft has the ability to travel with equal ease in water, on ice and, most impressively, through broken ice-congested channels. The propulsion system is efficient, durable and simple.

The design of the craft provides a stable and safe working platform under all conditions for either ice management or rescue activities.

The AST is capable of breaking fresh water ice unassisted over a specific range of ice thicknesses or it can operate in support of other icebreaking techniques as part of a harbour ice management system.

3. ICE MANAGEMENT PROJECTS WITH POTENTIAL FOR APPLICATION AT THUNDER BAY

Two other techniques for ice management with potential for application at Thunder Bay were also tested under the Transportation Development Centres ice management program. They are:

- patterned ice cutting;
- mechanical ice break and removal.

3.1 Patterned Ice Cutting (9)

3.1.1 Background

Based on actual experience in the Arctic it was anticipated that, during the last voyage of the 1982 shipping season to Little Cornwallis Island, NWT, the vessel M.V. Arctic would have difficulty berthing immediately adjacent to the dock because large pieces of ice broken by the vessel would become jammed between the vessel and the dock. These pieces would be too large to be washed away by the vessel's propeller and bubbler system. This circumstance prompted action to moderate the ice problem thereby ensuring that the vessel could dock as required.

The best information available revealed that some model testing had been done by Wartsila in Finland on the effects of certain cutting patterns on ice breaking. Following this information a test plan was developed using different herringbone patterns. (See Figure 3.1)

Effecting the ice cuts at Little Cornwallis Island proved to be relatively easy using John Deere 80-EV chain saws with regular log cutting chains. An average cutting rate of 1.3 m/min was readily achieved over the 3,600 m total length cut. Care had to be taken to ensure the cutting depths were not too deep so as to encourage water seepage into the slot. Initial depths of 35 to 40 cm were found to be too deep and subsequent cuts were maintained at depths of less than 30 cm. Some freezeback was still experienced after two or three days. Unfortunately, the result of this work could not be tested because the M.V. Arctic did not arrive. It was then decided to conduct model tests of the effect of cut-ice patterns on subsequent ice breaking by a vessel.

3.1.2 Model Tests of Ice-cutting Patterns (10)

Testing was carried out by Acres Consulting Services Ltd. in a refrigerated flume designed for the study of simulated ice conditions. The method used was based on the work of Dr. Garry Timco of the National Research Council in Ottawa. Systems were devised for cutting the ice to provide the required scale, 1:75. The 2 cm ice cover with 1.1 cm

120° cutting pattern

60° cutting pattern (seaward portion)

Figure 3.1 Herringbone Ice Cuts at Little Cornwallis Island

deep cuts spaced at 1 cm and 2 cm represented ice 1.5 m thick with 0.8 m cuts spaced at 0.75 m and 1.5 m respectively. (See Figure 3.2) The 1:75 scale of the M.V. Arctic was built by Acres. (See Figure 3.3)

A number of cutting patterns were tested including a parallel pattern and herringbone pattern with the apex towards and away from the approaching ship.

During each test a control area without cuts was used so that direct comparison could be made with the run in patterned ice. Photographs were taken of the ice in the vessel track following each run. These were blown up and digitized to provide data on the areas of ice pieces. These data were then used to determine the effectiveness of the cutting procedure in reducing the size of the ice pieces broken by the vessl. The force required to move the vessel was also monitored.

Figure 3.4 shows the type of results obtained. For this test a herringbone pattern with the peak away from the vessel was used for run A. Run B was the unpatterned control ice. In this case the number of pieces in the track was increased by 27% and their average size reduced by 34% when compared to the control track. There was also a reduction of 28% in the force required by the vessel to go through the ice.

3.1.3 Comment

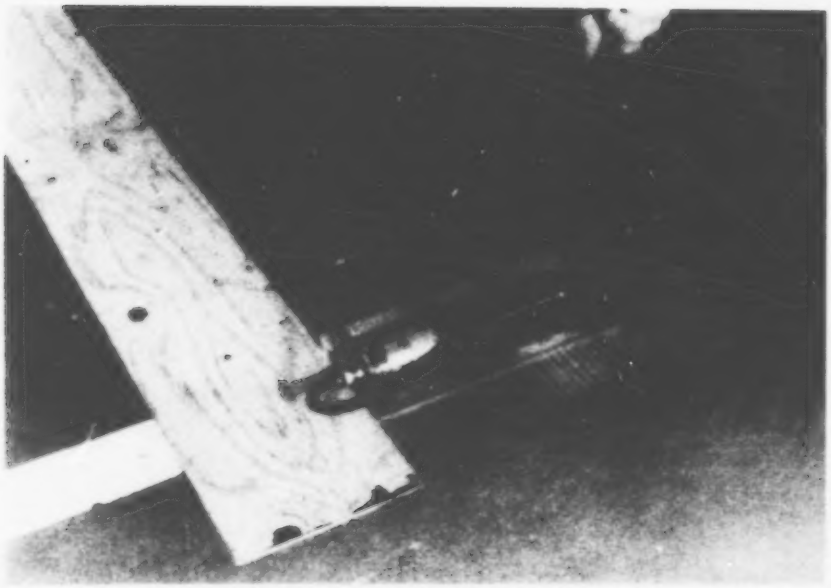
The model tests conducted indicated that cutting or slotting on ice cover can lead to a reduction in the size of the ice pieces broken by a vessel and could, therefore, facilitate berthing of vessels at docks in ice-covered waters. However, except for a very positive result that showed no reduction in the size of ice pieces when a herringbone pattern with its apex toward the approaching ship was used, none of the other patterns can be categorically said to be the most effective.

The modelling only tested the technique on ice of uniform thickness. In a real situation there is frequently a major build up of ice in the immediate area of the dock due to tidal effects or ice crushing by previous ships. Additionally, the experience of cutting the ice in the Arctic showed that freeze back of cuts could negate any advantage of the technique if ships' arrivals were delayed.

3.2 Mechanical Ice Break and Removal Techniques (11)

3.2.1 Background

A technique for ice removal was proposed by Mr. Erik Banke which offered a novel approach to clearing ice from piers. The technique, which is limited to landfast ice,



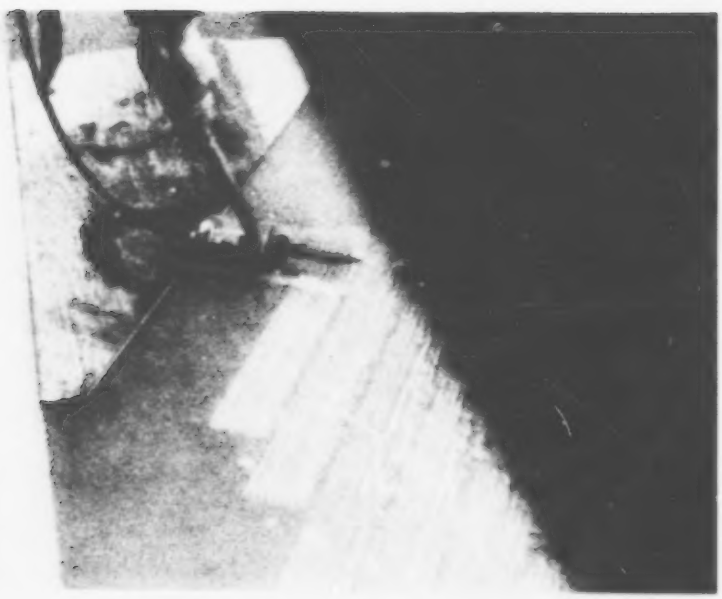


Figure 3.2 Model Test Cuts

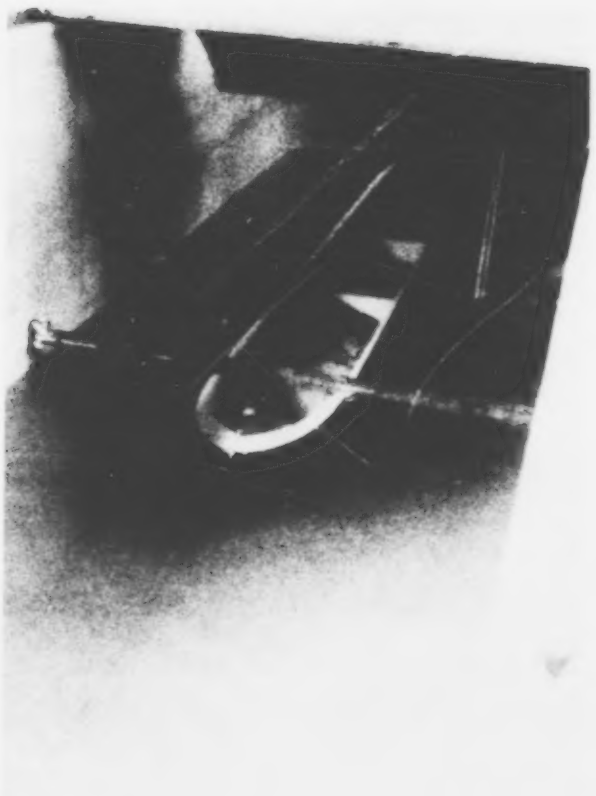
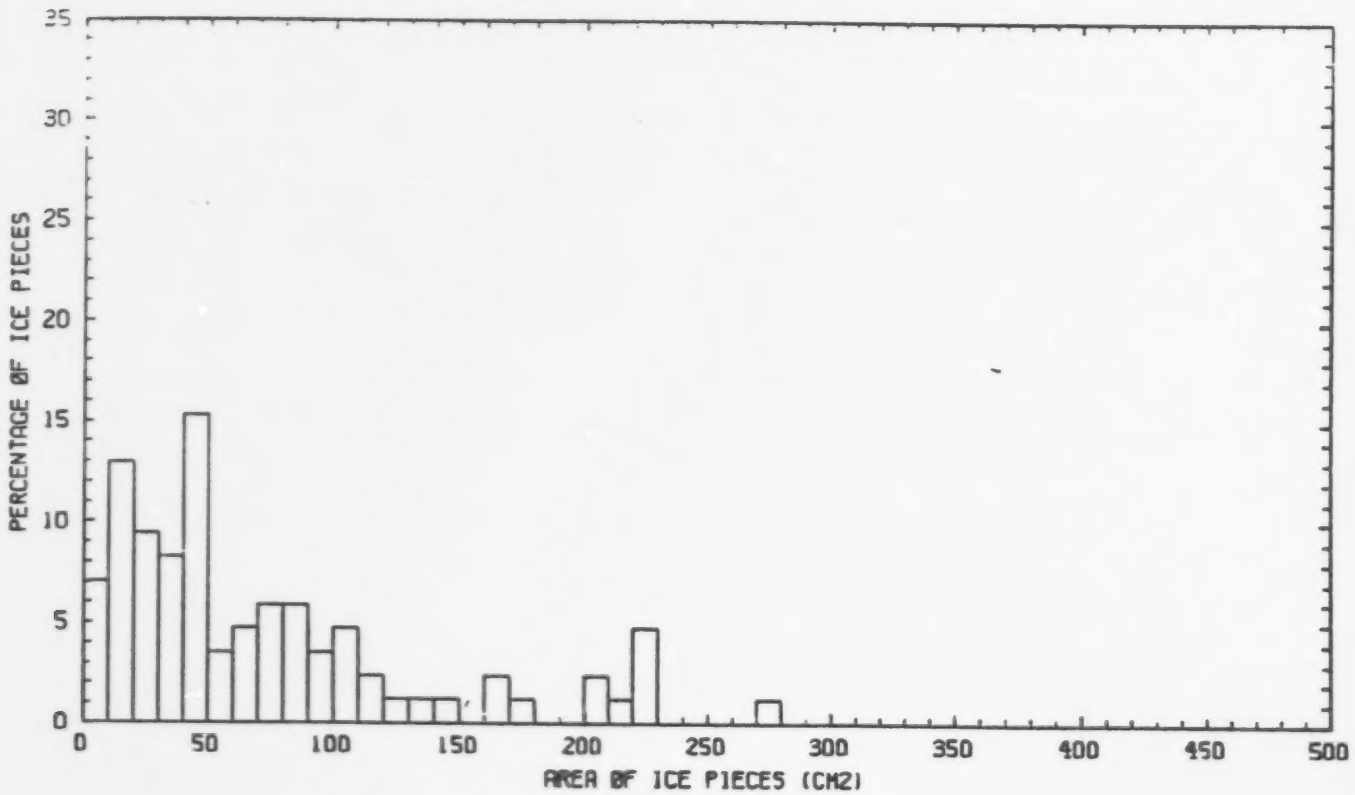


Figure 3.3 Model of MV Arctic in Test Tank



HERRING BONE - 2 cm SPACING
AWAY FROM VESSEL

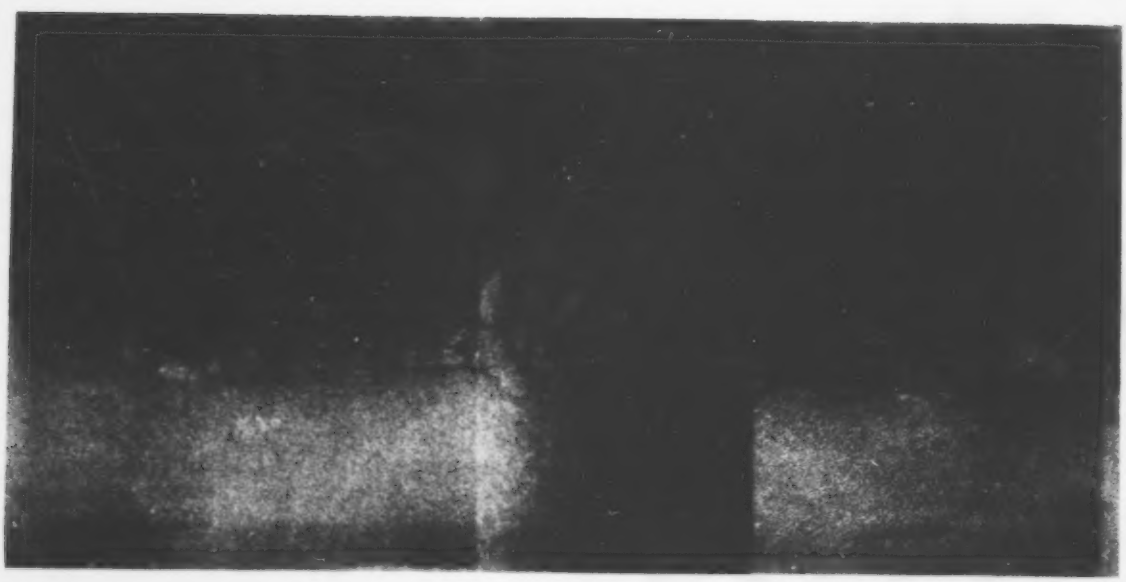


Figure 3.4 Typical Model Test Results

involves cutting the ice into blocks which are subsequently tilted and towed underneath the surrounding ice leaving an area of open water in which a ship can manoeuver. Figure 3.5 illustrates the concept. Three small scale tests were conducted by Martec Ltd. in harbours of Nova Scotia and New Brunswick which tested not only the concept but also a variety of implements and machinery that could be used to support the process. The results of this testing demonstrated the feasibility of the concept and developed several operational techniques which might be employed. A large scale test was then mounted at Cameron Beach near the town of Iroquois Falls, Ontario.

3.2.2 Description of Large Scale Test

Figure 3.6 illustrates the Cameron Beach test site. The test area was marked off in rows 6.125 m wide with each ice block 6.125 x 5.0 m. (See Figure 3.7) A Ditch Witch was used for all ice cutting except the 45° cut required for the leading edge of the ice block. A chain saw was used for this cut. (See Figure 3.8) A power driven ice auger was used to drill the holes necessary for the ice anchors. The various ice manoeuvering equipment developed during the small scale tests (see Figure 3.9) were well suited to the task of positioning the large ice blocks. Two types of towing equipment, a log skidder and a D-6 bulldozer with winch, were used for towing the blocks under the ice.

The technique developed during the small scale tests and illustrated in Figure 3.5 was initially used to move the blocks under the ice. The log skidder was used for towing during these operations. The procedure worked smoothly but the need to move the tripod and ice anchors was quite time consuming.

With the increased towing power available from the bulldozer, it was decided to use a single ice anchor located slightly forward of the center of the block with the tripod placed near the leading edge. (See Figure 3.10) Once the leading edge of the ice block was tilted below the surface the tripod was removed and the tow completed using the ice anchor.

Various other refinements were made to the technique. An ice guide was added once the tripod was removed to ensure the ice anchor stayed centred on the tow slot. With cold hard ice it was found that a single ice anchor could be used with no tripod. This was the fastest method of tilting and submerging the ice blocks.

Several difficulties arose: ice blocks broke, a wedge broke alongside the towing trench causing the tow line to jam, the ice blocks grounded on a sand bar as they were towed under the ice. None of these proved to be a major problem

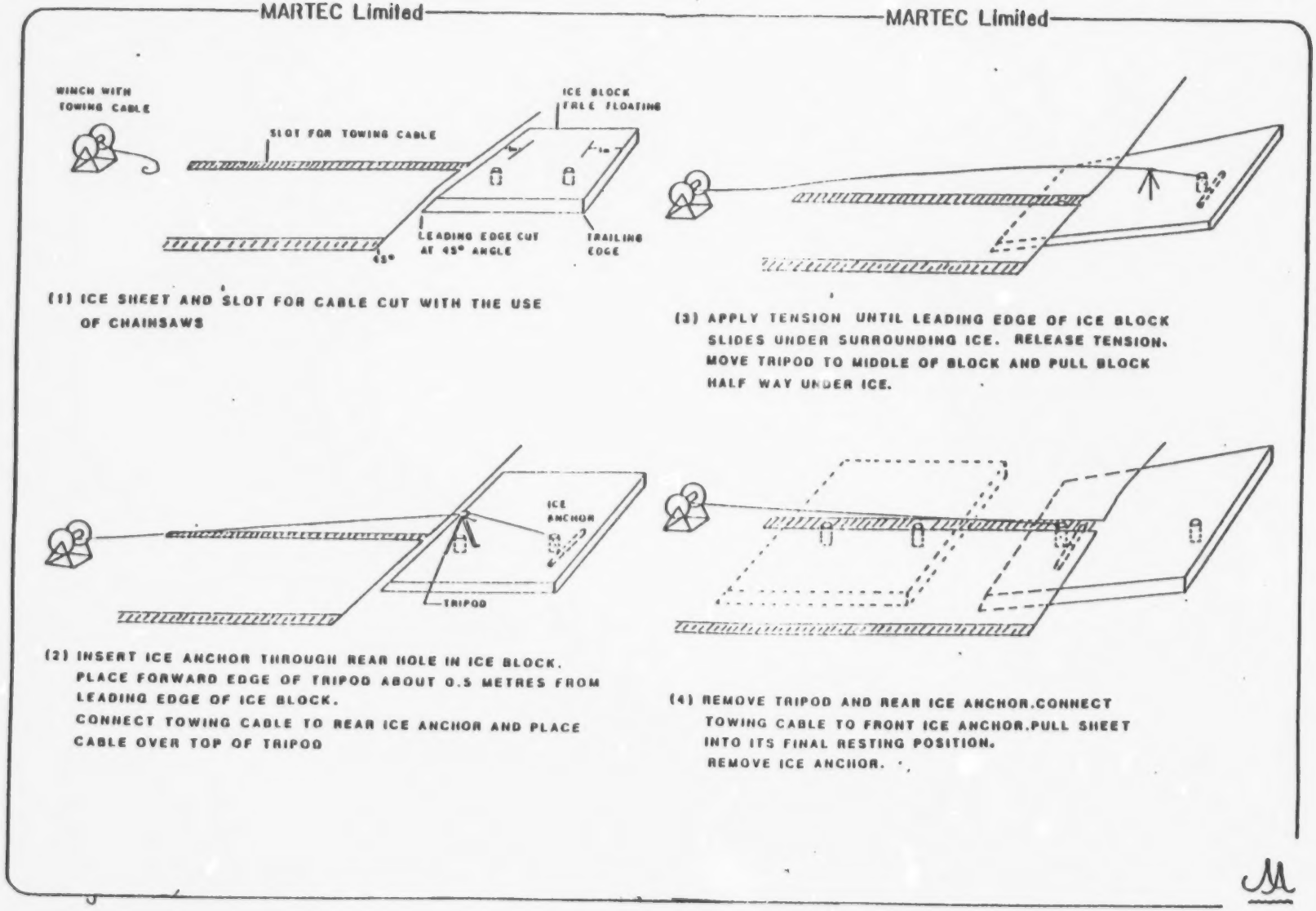

MARTEC Limited
MARTEC Limited
WINCH WITH TOWING CABLE
SLOT FOR TOWING CABLE
ICE BLOCK FREE FLOATING
LEADING EDGE CUT AT 45° ANGLE
TRAILING EDGE
45°
(1) ICE SHEET AND SLOT FOR CABLE CUT WITH THE USE OF CHAINSAWS
(3) APPLY TENSION UNTIL LEADING EDGE OF ICE BLOCK SLIDES UNDER SURROUNDING ICE. RELEASE TENSION. MOVE TRIPOD TO MIDDLE OF BLOCK AND PULL BLOCK HALF WAY UNDER ICE.
ICE ANCHOR
TRIPOD
(2) INSERT ICE ANCHOR THROUGH REAR HOLE IN ICE BLOCK. PLACE FORWARD EDGE OF TRIPOD ABOUT 0.5 METRES FROM LEADING EDGE OF ICE BLOCK. CONNECT TOWING CABLE TO REAR ICE ANCHOR AND PLACE CABLE OVER TOP OF TRIPOD
(4) REMOVE TRIPOD AND REAR ICE ANCHOR.CONNECT TOWING CABLE TO FRONT ICE ANCHOR.PULL SHEET INTO ITS FINAL RESTING POSITION. REMOVE ICE ANCHOR.

Figure 3.5 Application of Ice-block Under Ice Concept

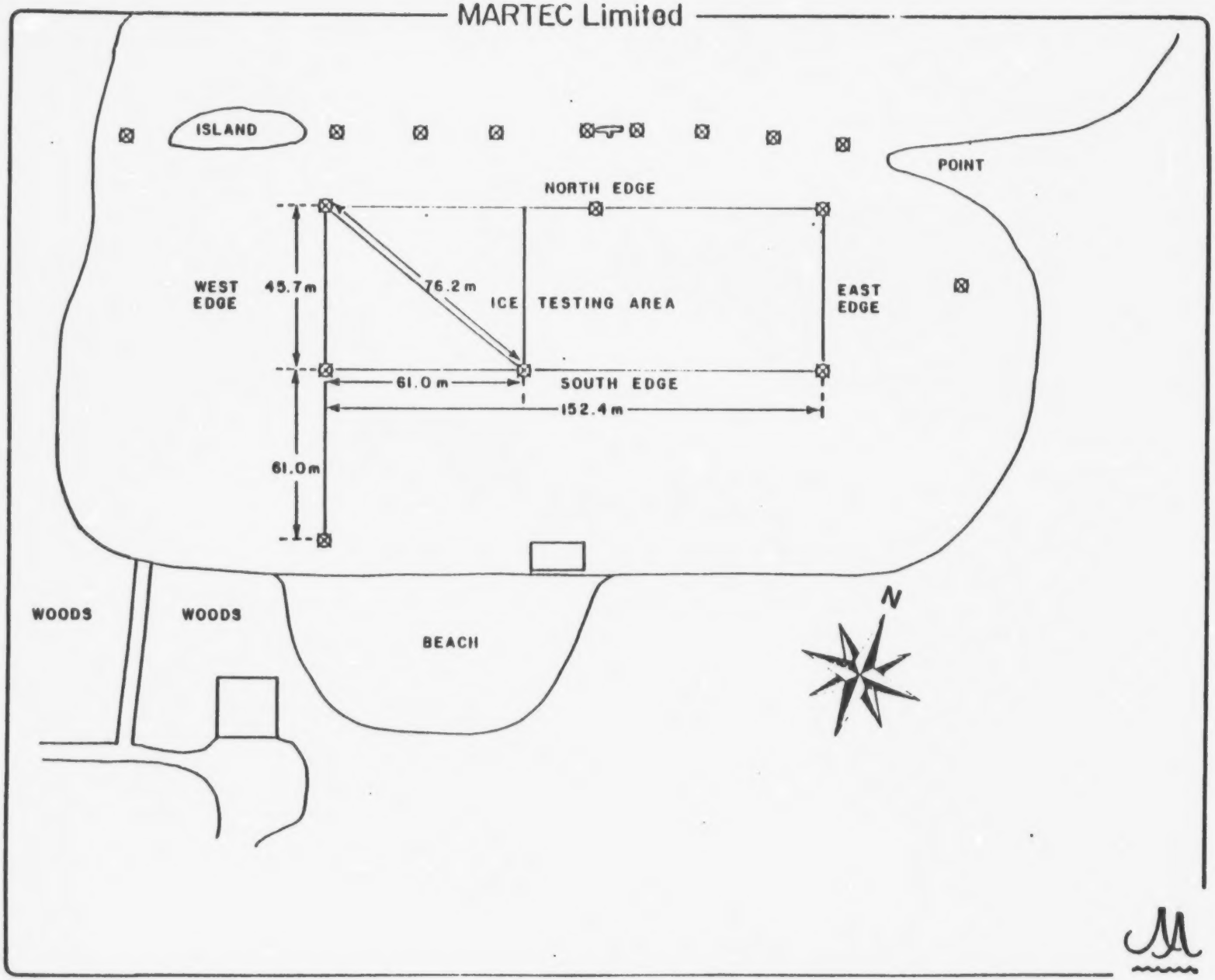


Figure 3.6 Dimensions Ice Testing Area

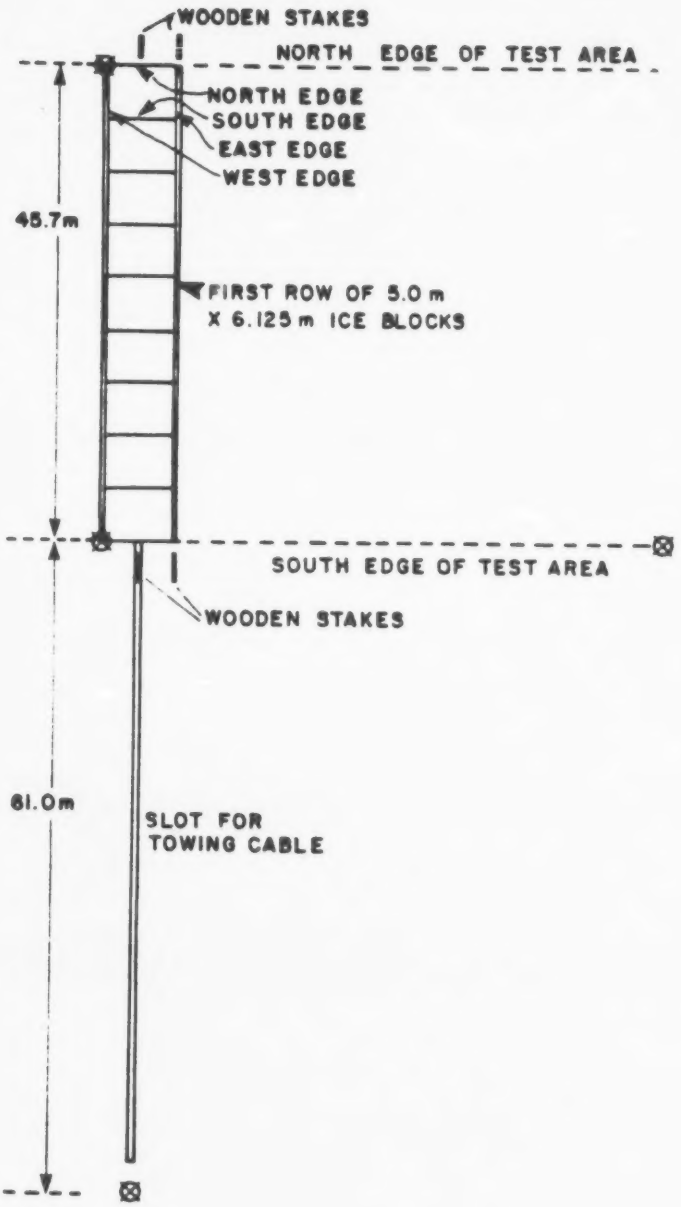


Figure 3.7 Dimensions of Ice Block Row

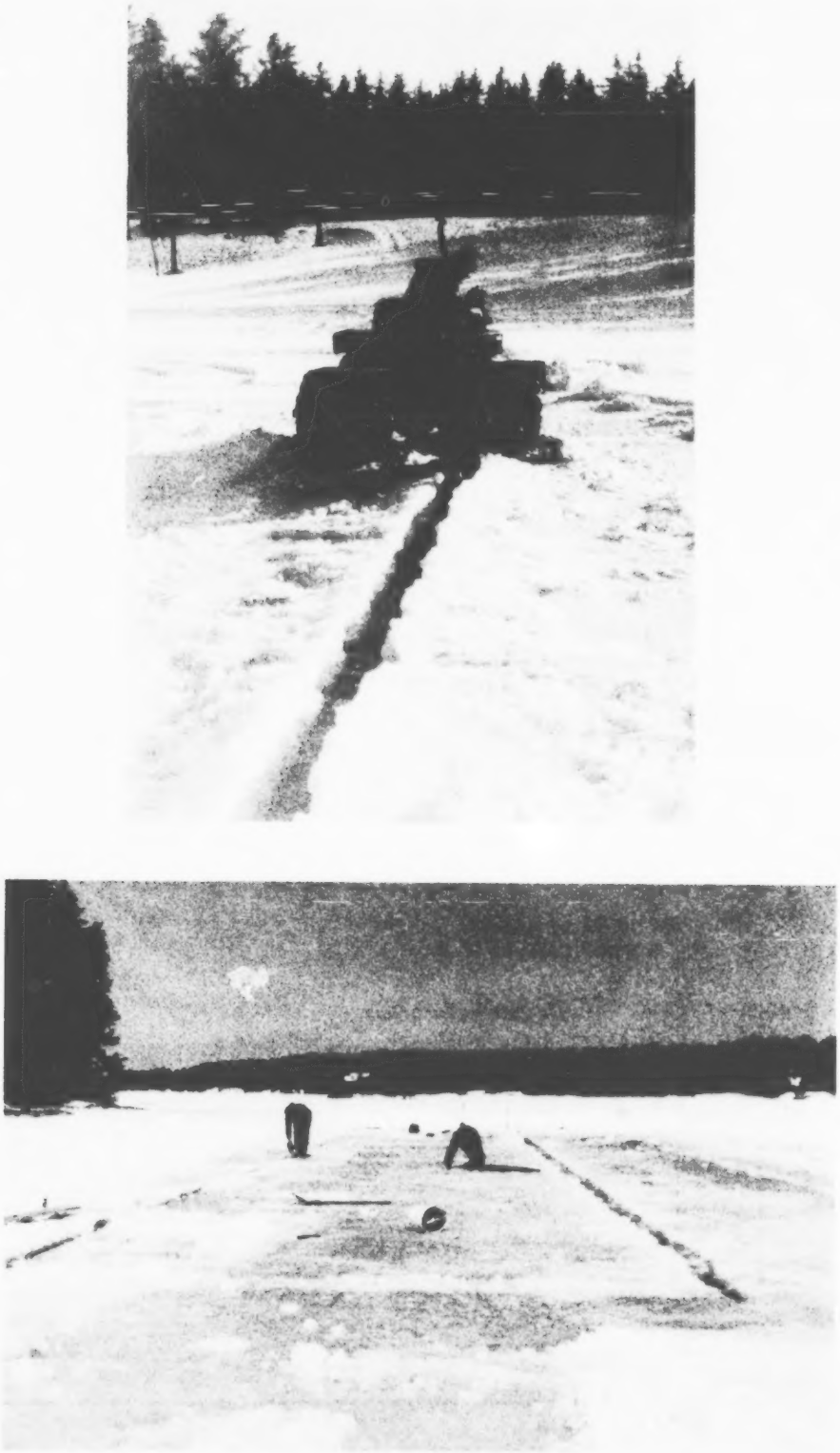


Figure 3.8 Ice Cutting Using Ditch Witch and Chain Saw

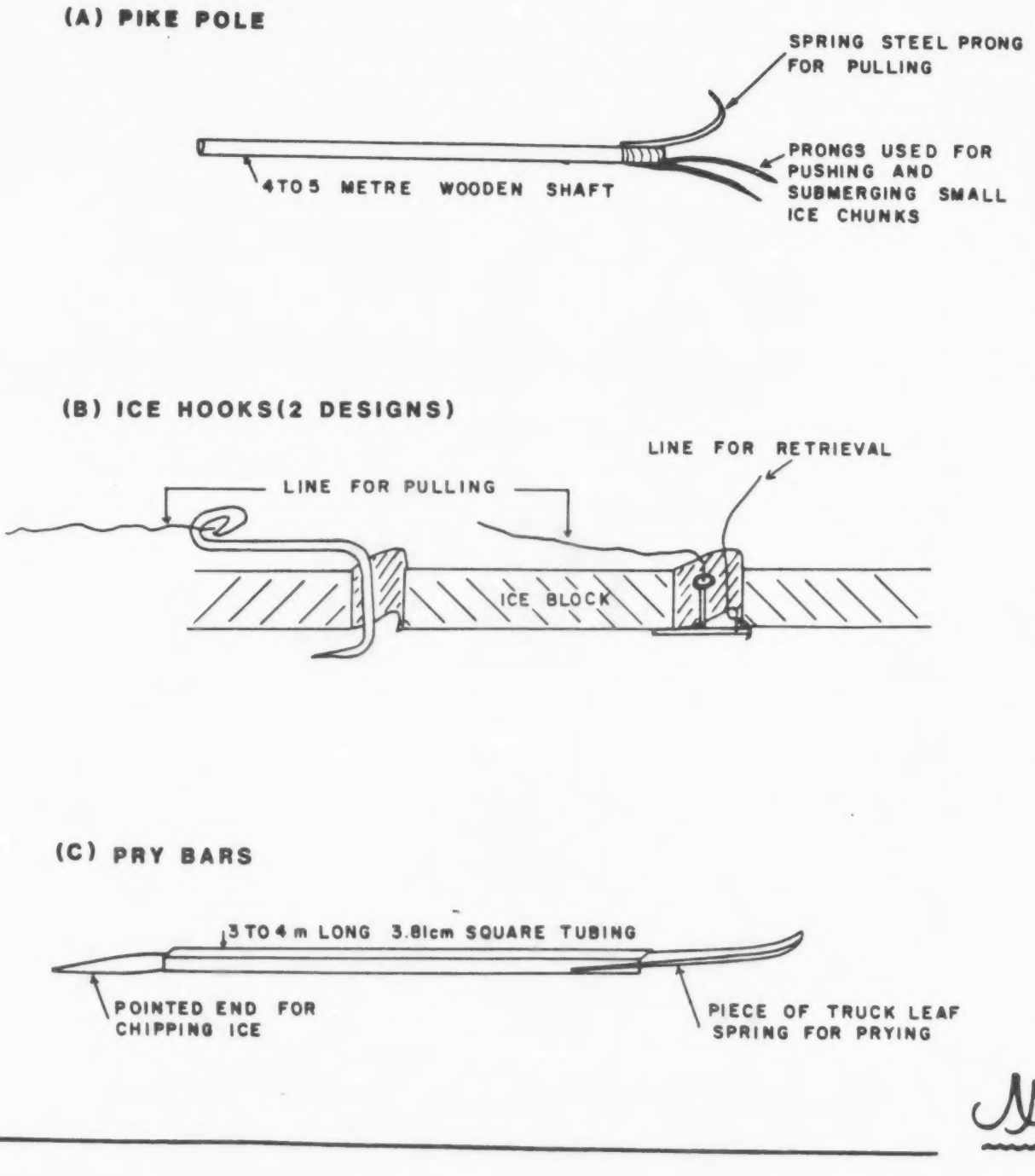

(A) PIKE POLE
SPRING STEEL PRONG FOR PULLING
PRONGS USED FOR PUSHING AND SUBMERGING SMALL ICE CHUNKS
4TO5 METRE WOODEN SHAFT
(B) ICE HOOKS(2 DESIGNS)
LINE FOR RETRIEVAL
LINE FOR PULLING
ICE BLOCK
(C) PRY BARS
3TO4m LONG 3.81cm SQUARE TUBING
POINTED END FOR CHIPPING ICE
PIECE OF TRUCK LEAF SPRING FOR PRYING

Figure 3.9 Ice Manoeuvering Equipment

Figure 3.10 Submerging Ice Block with Tripod

and were readily coped with using the equipment at hand and the experience gained over the five days of the test.

The actual area cleared before warmer weather halted the test was approximately 46 x 57 m. A removal rate of 20 to 24 blocks a day was achieved in the final 2½ days of testing compared with a rate of 7 blocks per day on the first day. The costs incurred are listed in Table 3.1.

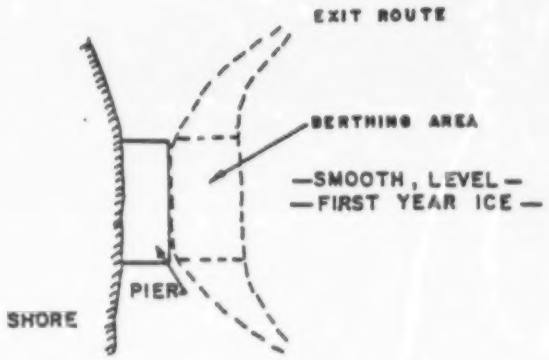
3.2.3 Comment

The towing of an ice block under the surrounding ice to expose an area of open water has been shown by this test to be technically feasible using commercially available equipment. Figures 3.11 and 3.12 illustrate two scenarios where these techniques could be applied. Extrapolating from the cost experience of the test, the unit cost of this method of ice clearance would be $\$1.53/m^2$.

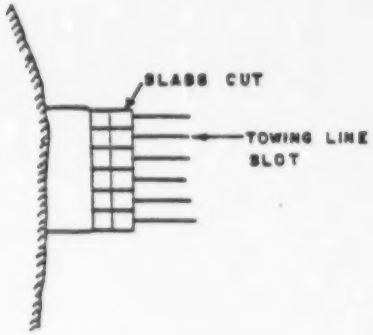
Leased Equipment	Daily Rate
1 Ditch Witch	$ 175
1 bulldozer with operator	440
1 electric generator	25
1 snowmobile	35
2 chainsaws	70
1 ice auger	25
	770
Personnel	
1 Field supervisor	290
4 Field personnel	1,000
	1,290
Supplies	
45 litres gasoline	20
2 litres chainsaw oil	5
Miscellaneous hardware	50
	75
Services	
Accommodations (5 people)	100
Meals	170
Transportation	95
	365
TOTAL DAILY COST	$2,500

Purchased Equipment	Cost
Guide post	$ 150
Cables and hooks	500
Rope	100
4 ice anchors	500
1 tripod	300
Pike poles, prybars, etc.	300
Timbers, stakes, etc.	150
TOTAL COST	$2,000

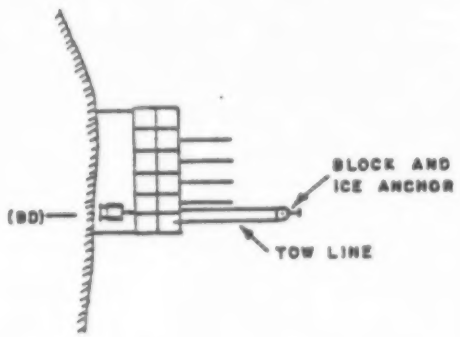
Table 3.1 Cost Estimate for Ice Removal Operations



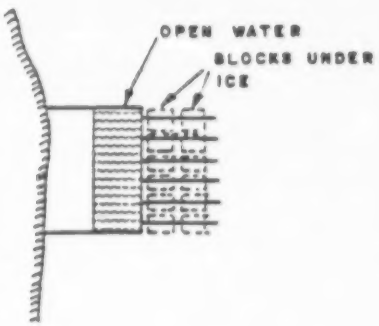
(A) PLAN VIEW OF PIER, HARBOUR CONDITIONS.



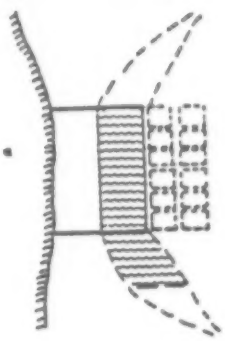
(B) CUTTING OF ICE AND SLOTS FOR TOWING CABLE.



(C) TOWING BLOCKS UNDER ICE USING BULLDOZER (BD) ON THE PIER.



(D) BLOCKS UNDER ICE.



(E) CUT ENTRY CHANNEL AND TOW BLOCKS UNDER. CUT EXIT CHANNEL (IF NECESSARY) PRIOR TO SHIP DEPARTURE.

Figure 3.11 Sequential Procedure for Clearing Harbour Ice

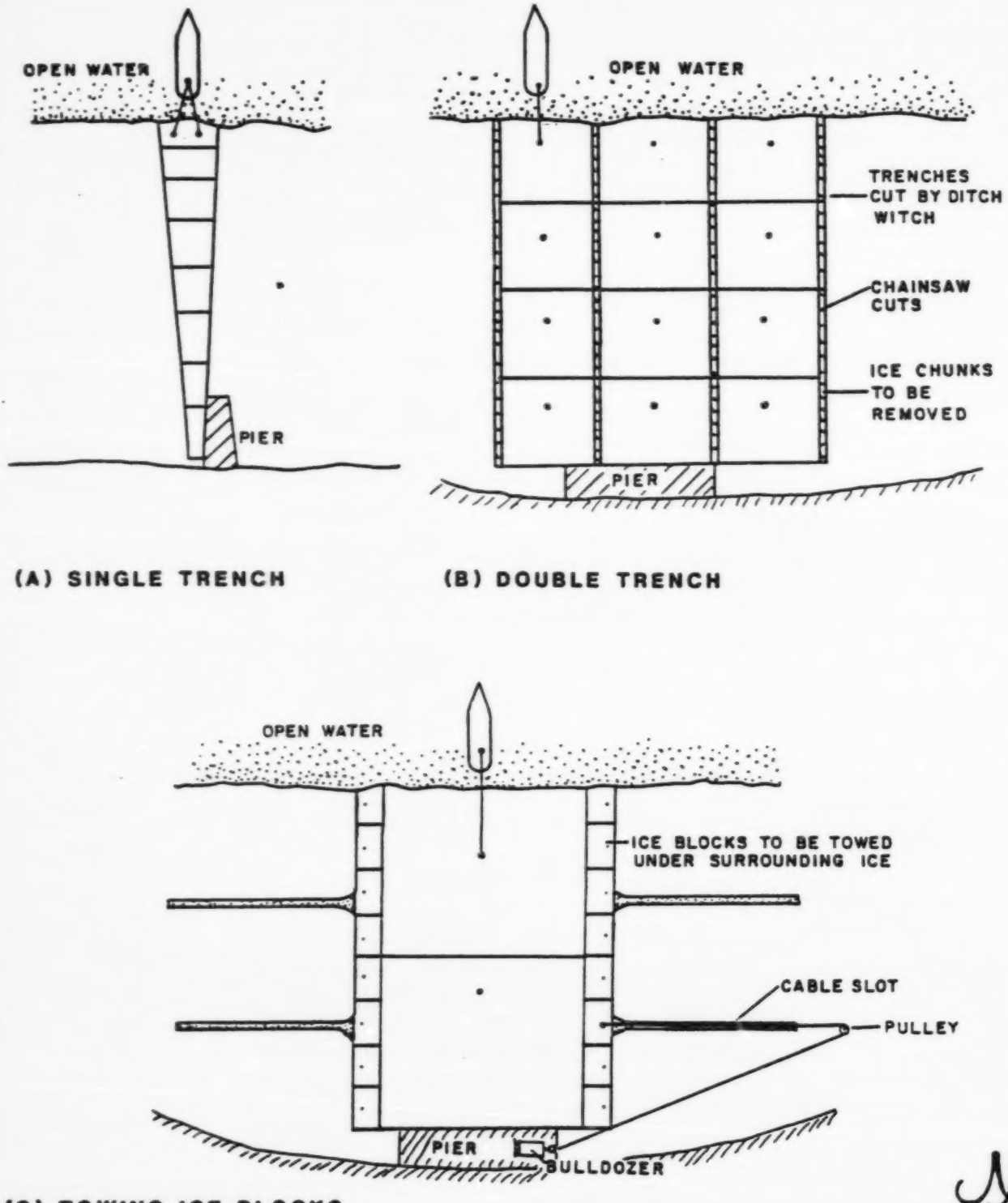


Figure 3.12 Method for Removing Ice Near Open Water

4. CONCLUSIONS

The work undertaken in the various ice management projects has provided the Thunder Bay Harbour Commission with a variety of reliable techniques to ensure that the slips in the port are free of ice so that loading operations can begin as soon as the ship channels are cleared in the spring. Additionally, the understanding of the natural heat available for ice melting has been substantially increased.

4.1 Air Bubbler Systems

The use of an air bubbler system to free a slip of ice has been demonstrated to be effective. The evolution of the system configurations from 1979 to 1985 has moved the technology from an experimental concept to a reliable tool for ice managment. The results of this program have provided potential users with three bubbler configurations to choose from as follows:

- line air bubbler;
- piston air bubbler;
- rake air bubbler.

The basis for choice rests on the configuration of the slip, the operational procedures of the user and the cost of the system. In fact, any given system may use both line bubblers and piston or rake bubblers.

a) Line air bubblers

The conventional line air bubbler is always at risk from ship operations and from silting-up of bubbler holes; hence, maintenance costs are sufficiently high to make this system the least cost effective. The opportunities to install a permanent line air bubbler as part of new slips or during the refurbishing of old slip faces, as occurred in 1985, results in a reliable bubbler system that is actually the most cost-effective of the systems tested.

b) Piston air bubblers

Piston air bubblers offered a good alternative to line bubblers for mid-slip installations. With appropriate deflectors installed, their maintenance free operation and their ability to operate on low pressure blowers make them very attractive from a cost point of view if the capital expenses can be amortized over a period of five years. The units must be removed from the slip before ship operations start in the spring.

c) Rake air bubblers

The rake bubblers also offer a good alternative to line bubblers for mid-slip melting. For some operations they have an advantage over piston bubblers in that they are moved along the slip as melting progresses.

4.2 Modelling of Bubbler Systems

The reporting on the bubbler projects has provided a computer model aimed at optimizing the design of a system for individual slips and a model to predict the length of time required for the system to operate in order to open the slip. Correlation of the prediction model and the actual results is within 7%.

4.3 Thermal Reserve of Slip

The detailed slip temperature monitoring conducted has demonstrated that the melting of ice is not dependent on the thermal reserve of the slip water itself. There is a considerable transfer of heat to the slip from the earth beneath the slip and from the deeper water in Thunder Bay.

4.4 Dock loading

The experimental and analytical techniques developed to measure the loads on the slip structure produced by véssel icebreaking activities can probably be transported to describe order-of-magnitude pressures applied on any structure located around a navigation channel. The research carried out at Thunder Bay serves as a first step for more comprehensive research that would evaluate other variables, eg. vessel distance from structure, bow shape, structure shape.

4.5 Ice cutting

Results from the ice cutting experiments indicate that there is limited application of this technique to the Thunder Bay area. The ships calling at Thunder Bay would not be operating in the slips when there is any substantial degree of ice cover as is the case in Arctic ports. Additionally, the modelling work done produced mixed results. More investigation of the technique is required before it could be confidently used in an ice managment program.

4.6 Mechanical Ice Breaking and Removal

This novel technique may have practical application in slips at Thunder Bay for the removal of a centre ice section into the harbour. It might be used in conjunction with line air bubblers on the slip face. However, the logistics

of blending the ice cutting and tow procedures with bubbler operations in the slip and ice breaker operations in the harbour would have to be carefully drawn.

4.7 Cost Comparisons of Ice Management Systems Used at Thunder Bay

The cost comparisons for certain bubbler configurations are given in Table 3.1. Two other sets of figures have been developed for clearing ice from slips; one set for a permanent bubbler system (7) and one set for the ALEXANDER HENRY/ ACIB combination.

Table 4.1 combines the various cost figures available. The costs shown for the ALEXANDER HENRY/ACIB are taken from comments from J. Laframboise, TDC as follows.

> "Assuming that the slip area to be cleared of ice in Thunder Bay is 200,000m^2 (10 slips of 50m x 200m), the ALEXANDER HENRY/ACIB combination could clear them of ice (or at least shatter the ice sufficiently not to hinder ship movement) in about two days, based on the 1984 experiment. Thus if one allows 20% of the ACIB operating time in a given season to this work, the ice clearing (based on a $500,000/year ACIB cost) would cost $\$0.50/m^2$.
>
> If the ACIB was used just for this operation, with consequent savings in maintenance and with the use of a tugboat, the cost would be below $\$2.50/m^2$, still inferior to that of bubbler systems."

SYSTEM	PROTOTYPE 10-UNIT AIR CANNON	5-UNIT AIR CANNON	PROTOTYPE RAKE	PROTOTYPE LINE	PERMANENT (SMALL) BUBBLER	PERMANENT (LARGE) BUBBLER	ACIB
ICE AREA CLEARED	2750 m^2	(est.) 1375 m^2	1100 m^2	n/a (est.approx.) 500 m^2	690 m^2	4358 m^2	200,000 m^2
PROTOTYPE TOTAL COST	\$18.25/m^2	(est.) \$20.07/m^2	\$ 9.45/m^2	(est.) \$56.02/m^2	n/a	n/a	
AMORTIZED ANNUAL COST	\$ 4.88/m^2	\$ 5.82/m^2	\$ 5.98/m^2	\$19.84/m^2	\$ 8.83/m^2	\$4.77/m^2	\$2.50/m^2

Table 4.1 Cost Comparisons Per Unit Ice Cleared for Ice Management Systems

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